THE HEAT TREATMENT OF TOOL STEEL

HARRY BREARLEY

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AN ILLUSTRATED DESCRIPTION OF THE PHYSICAL CHANGES AND PROPERTIES INDUCED IN TOOL STEEL BY HEATING AND COOLING OPERATIONS

BY

HARRY BREARLEY

SECOND EDITION

WITH ILLUSTRATIONS

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OUR DAYS TOGETHER

PREFACE

THE following pages are intended to be helpful to the trained artisan and foreman, whose business it is to produce steel objects and tools for various purposes. Also to the merchant, manufacturer's representative, and other official, who frequently meet complaints which they would like to fathom, and are often called upon to assume a knowledge of the properties of steel somewhat out of proportion to the opportunities afforded by the daily routine of their business.

In the steel trade, perhaps more than in any other trade, the consumer looks to the manufacturer to furnish instructions about all materials and processes relating to the properties of steel. This state of affairs arose quite naturally at a time when the means at our disposal for investigating and classifying tool steels were confined exclusively to an examination of the fractured ingot or bar. This kind of examination the steelmaker developed into an art, which he practised with wonderful proficiency and accuracy long before the science of analytical chemistry was competent to replace his " tempers " by percentages of carbon.

From the combined experience of the maker and user of steel there arose eventually a system whereby material of approximately the same kind was supplied, from whatever source it came, for the same purpose. As this system was based on appearances intelligible only to the competent steelmaker, it was inevitable that he should, in most cases, become arbiter and judge as to defects and remedies incidental to the heat treatment of tools.

Although the small ingots into which tool steel is originally cast are still for the most part graded according to the appearance of their fractured surfaces, it has long been possible, for general purposes, to replace

arbitrary signs denoting "tempers" by definite figures representing chemical composition. In this form the "temper" of a steel bar, and its fitness for any particular purpose, may be understood and appreciated by the user quite as intelligently as by the maker. The observant toolmaker, therefore, assisted by his personal experience, should be equally as competent as the steelmaker to face his own difficulties.

The ultimate value of a tool may depend as much on the manner in which it is worked into its finished shape, as on the material from which it is made. The skill and knowledge of the toolsmith and hardener must therefore always be taken into account. If for any reason whatever these cannot be relied upon, then softer steels which are not so readily overheated in forging, or cracked in hardening, are invariably introduced at the cost, and finally to the dissatisfaction, of the tool user.

Reference is repeatedly made in the text to the value of patient observation and careful experiment, in however modest a degree they may be exercised. The writer hopes that the subsequent pages, aided by these twin brothers, will enable the toolmaker to improve his products, and also to locate and avoid some of his troubles. He may at any rate easily convince himself that the destiny of his tools is not altogether in the hands of the steelmaker, and that not all defective and broken tools can justly be ascribed to bad steel, but are often due rather to various causes which may be detected and remedied.

In preparing a second edition of this book, it was permissible, as the author is less restrained than formerly, to refer at greater length to steelmaking operations; first, in order to state a few principles which are sometimes overlooked or ignored by the steelmaker himself, and, secondly, to disclose limitations in the art of steelmaking which account for a considerable number of defective tools.

Alloy steels generally and high-speed steels in particular, are more fully dealt with. In this branch of the subject much is still uncertain; many first impressions

have turned out to be false, and what we now take as correct or extremely probable may not survive criticism and further experiment. The chapter on Case-hardening is omitted because it has been made the subject of a separate book.

It is hoped that the added pages may be useful to the maker as well as the user of tool steel, as the author is indebted to both for helpful suggestions and criticisms; especially to his friend and colleague, Fred Atkinson, who has also kindly read the proofs.

H. B.

186 Attercliffe Road,
Sheffield,
April 1916.

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STRUCTURE AND CLASSIFICATION

THE toolmaker is not at all interested in the question "What is steel?" from the point of view of learned societies and congresses. He is, however, very much concerned with the differences which confer on this material the properties of a good sate, on that the qualities required by a drill, and on the other the virtues looked for in a turning tool.

It is important, also, that he should appreciate the changes brought about in the physical properties of steel by case-hardening, water-quenching, tempering, annealing, and so on. He may further, once the rudiments have been understood, proceed to a consideration of the principles underlying the properties of the newer alloy steels of which one now reads so much and understands so little. He may ultimately do much to dispel our ignorance of many material things which can be more favourably observed in the shop than in the laboratory, and more sharply corrected by experience than by our too-little-suspected theories.

CRYSTALLINE STRUCTURE.

Every mechanic has seen a brass or a steel casting, a burnt furnace-bar or some other metal object snapped in two, and has observed the coarse, staring kind of fracture made up of crystalline particles, having sharp edges and shining flat faces, as represented in Fig. 1.

This kind of structure on a greater or smaller scale is present in every metal or combination of metals, although the ideal geometrical forms to which the crystalline grains

approximate may vary. Owing to rapid cooling or the pressure exerted by the hammer or rolls, the crystalline grains are often very ill defined and hardly distinguishable to the naked eye. All commercial kinds of steel belong to this category and must be examined by means of a microscope in order to elucidate their structure.

MICRO-STRUCTURE.

To see the collection of small crystals packed into a piece of forged metal no larger perhaps than a good-sized pin's head it is necessary to apply high magnifying

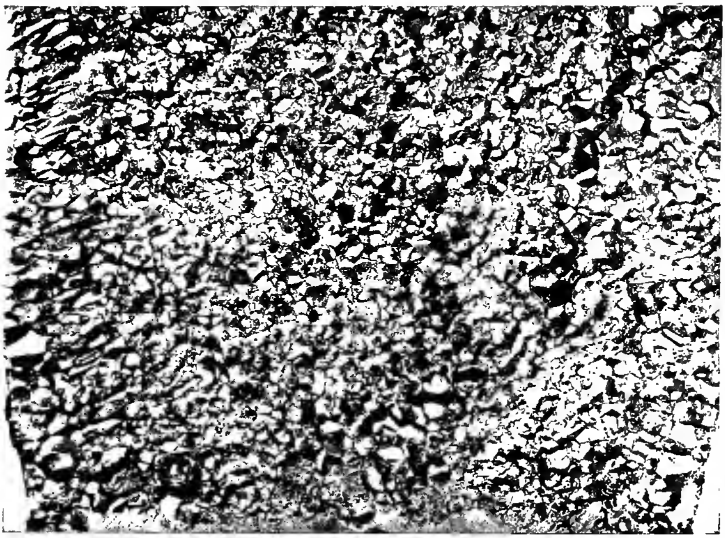

FIG. 1.—Crystalline fracture of large steel casting. Linear reduction about one-third.

powers to a flat surface. This means, of course, that in a section through the minute crystals there will be seen something like Fig. 2, which represents the microstructure of pure iron.

The resistance of such an agglomeration of unit crystals either to steadily applied stresses or impact forces will depend—

1. On the strength of the material of which the grain consists.

2. On the cohesion between the respective grains.

In pure metals which have been well wrought the former is generally quite as easily overcome as the latter, though cohesion between the grains is usually lessened by improper heat-treatment and frequently very much so by the presence of impurities.

In some cases it happens that when one metal is alloyed with another it does not in any way interfere with the form of the crystalline grains. A silicon-iron alloy, for example, containing, say, 3 or 4 per cent. of silicon, would

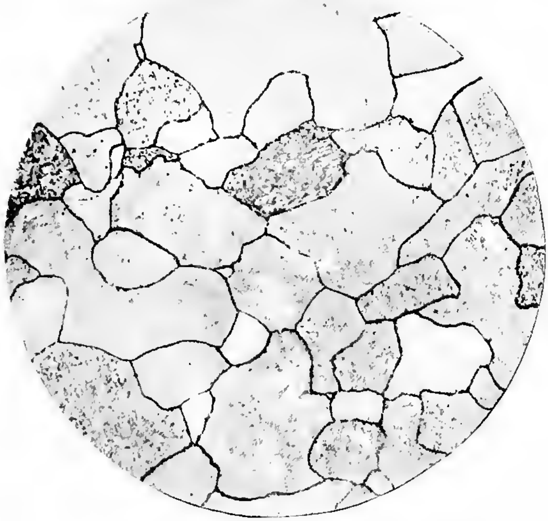

Fig. 2.—Microstructure of pure iron. Photo by Guertler.

appear exactly like Fig. 2, except that, after similar treatment, the grains would be larger. The addition of a small amount of chromium would also be indistinguishable in the form, though it would decrease the size, of the grains. In the study of alloys of this kind, many of which exist, the microscope is not especially helpful. On this account the presence of silicon, manganese, chromium, nickel, and some other elements commonly added to steel are not directly distinguishable. On the other hand, some elements, on being alloyed with a second, can easily be detected even in minute quantities, and it is thus possible to observe microscopically the structural

changes taking place as the relative amounts of the two original substances are varied. In considering carbon and iron as a particular example of this class of alloys, we shall see more clearly than in any other way how wrought iron becomes transformed into steel.

IRON AND CARBON.

The effect of introducing even less than one-tenth of one per cent. of carbon into iron is easily visible in a properly prepared specimen examined with the microscope. In addition to the regular polyhedric crystals,

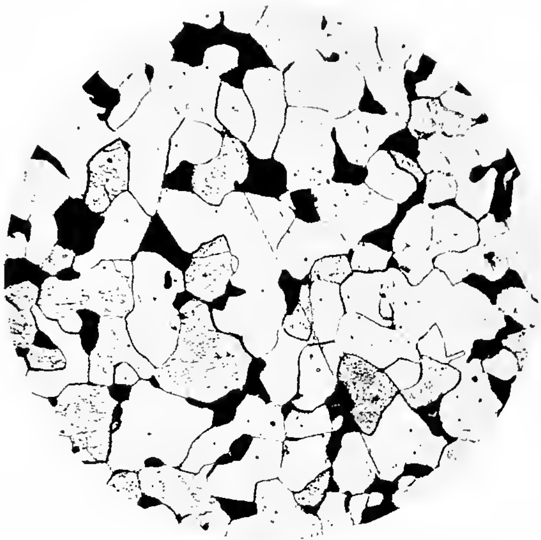

FIG. 3.—Iron containing 0·15 per cent. of carbon. Magnified 100 diameters.

which are practically alike, there now appears a number of dark areas as exemplified by Fig. 3. Practically all the carbon introduced is confined to these dark areas, the remaining portion of the observed field consisting as before of pure iron, which as a micro-constituent is known as ferrite.

PEARLITE.

If the dark areas were highly magnified and the steel in which they exist had been slowly cooled from a good red heat, say 800° C., then they would have the appearance of black and white lines arranged alternately and roughly parallel to each other. This arrangement is

common amongst metallic alloys, and is characteristic of what are called eutectoids. At present the object is merely to call attention to a fact of which we have later to make some use, and not to discuss the cause and condition of eutectoids, which is somewhat outside the scope of our purpose. It should, however, be remarked that the striated appearance of the dark areas seen in Fig. 4 is really due to a compact arrangement of alternate plates of pure iron and carbide of iron (Fe_3C) after selective etching.

When the striation is sufficiently well defined, as is usually the case in annealed tool steel, it breaks up light-waves just like the surface of a pearl and for the same reason. On this account the dark areas when first observed by Dr. Sorby were called the "pearly constituent," and are now spoken of briefly as "pearlite."

All mild steels, then, considered microscopically, are composed of ferrite [1] and pearlite.

The relative areas occupied by these constituents in a piece of slowly cooled steel depend on the amount of carbon present. Fig. 3 is a typical appearance of a steel containing 0·15 per cent. carbon; Fig. 4 represents a steel containing 0·45 per cent. carbon, and Fig. 5 the appearance of a steel containing about 0·75 per cent. carbon, in which case the pearlite areas are completely surrounded by envelopes of ferrite.

From this point onwards the ferrite envelope becomes thinner as the percentage of carbon introduced becomes greater, and ultimately, when the carbon reaches approximately 0·90 per cent., the ferrite disappears; that is to say, it becomes entirely monopolized by the carbon to form pearlite.

The point in composition at which free ferrite ceases to exist in steel is, as we shall see later, of exceptional interest to the toolmaker, and, like many other industrial

[1] For the sake of directness we are assuming that steel is simply an alloy of iron and carbon. As a matter of fact, steels always contain small amounts of silicon, manganese, sulphur, and phosphorus, which do not, however, greatly interfere with the micrographic appearance.

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steel, and consequently brittle. It is very finely dispersed and intimately mixed with the iron so long as the amount of carbon does not exceed one per cent., but any excess beyond this exists in a comparatively coarse state.

PHYSICAL PROPERTIES.

From these considerations, and attentive observation of Figs. 2 to 7, it is obvious that the hardness of steel will increase as the pearlite grains occupy a larger portion of the material. It is equally obvious that the toughness will decrease as the ferrite grains, which are composed

FIG. 7.—Free cementite needles in case-hardened steel. Photos at 100 diameters.

of soft flexible iron, become less. But the toughness may still be considerable, so long as each small plate of hard carbide is cushioned between two plates of soft iron—that is, until the amount of carbon approaches one per cent.

When the carbide is free to form comparatively large plates, or to form brittle envelopes separating each grain from its neighbour, the intergranular cohesion is enormously weakened. We are able, therefore, to take advantage of the great hardness of steel containing free carbide (cementite) only for such purposes as involve no sudden or violent blows, as, for example, turning-tools,

razors, scythes, etc. If hammers or cold sates were made from such steels they would, as may easily be imagined, quickly break up along the brittle crystalline junctions.

For such purposes as require tools to withstand rough usage, and at the same time demand a hard cutting edge, a steel containing, for obvious reasons, little or no cementite must be chosen; whilst for many purposes, such as drop-forging dies, cold sates, boiler-makers' snaps, etc., the toughness of the objects may be still further increased by using much milder steels, and sacrificing that portion of the hardness which is not imperative.

GRADING STEEL.

Having seen that the efficiency of a tool depends to a great extent on the kind of steel from which it is made, it is easy to understand why the steelmaker usually requests the purchaser to state the purpose for which the required steel is intended, as it is in practice by no means very rare to find tools made from quite unsuitable material otherwise excellent in quality. In order to avoid such errors it is customary to indicate by label and stamp the purpose for which any particular bar of steel may be satisfactorily used. The table on p. 10 is a representative list of such purposes, together with the approximate amount of carbon present in the respective steels, and the older names by which the tempers were formerly distinguished.

TEMPER.

All carbon steels are classified according to their temper and quality. Temper is used by the steelmaker (as a noun) to denote the natural degree of hardness, which can be varied by the introduction of more or less carbon.[1] The natural hardness can, of course, also be varied by introducing manganese, chromium, tungsten, etc., but the word had acquired a definite meaning before the value

[1] The use of the word "temper" (as a verb) in a somewhat different sense is justified and quite well understood by the practical hardener. But the use of the word "temper" by translators, and persons more or less remotely connected with the usages of the steel trade, to denote a change brought about by quenching from a high temperature, which every craftsman calls hardening, leads to confusion and should be abandoned entirely.

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II

CRUCIBLE STEEL—RAW MATERIALS

Crucible steel was first made on a commercial scale by Huntsman in 1740. Huntsman's process consists essentially of carburizing bar iron and then melting the carburized iron, after breaking it into small pieces, and casting it into ingot form. Only a comparatively small quantity of tool steel is now made in that manner, the much larger part being made by charging wrought iron or scrap along with some carburizing agent, such as charcoal or white pig iron into the melting-pot. Cast steel was made by this latter process by Reaumur in 1720, but apparently on an experimental scale only.

To carburize, or convert, wrought-iron bars costs about thirty shillings per ton, and where this cost is an unimportant part of the total cost the process is not entirely superfluous. Converted bar iron containing, say, $1\frac{1}{4}$ per cent. carbon can be easily melted in crucible melting furnaces. On the other hand, uncarburized bar iron can be melted only with difficulty, and it becomes liquid under ordinary circumstances only after it has become carburized by the charcoal or pig iron charged along with it into the crucible.

Melting operations.

This distinction between the melting of converted iron and bar iron is important, because it explains certain difficulties and defects which arise occasionally in alloy steels. The Huntsman process is purely a melting operation. The modified process, now most frequently used, requires higher temperatures and is partly a melting operation and partly an operation requiring the less-fusible material (wrought iron or alloy) to be dissolved in that part of the charge which first becomes molten.

This latter stage in the melting operation may be

compared broadly to the dissolving of sugar in tea. Given time and intimate contact between the solid and liquid portions it is a simple matter to produce a homogeneous fluid. But whilst it is easy to stir tea it is somewhat impracticable to stir molten steel in a crucible, and small pieces or particles of the less-fusible wrought iron or alloy conceivably may and sometimes do remain unmolten and become part of the ingot, with consequences more or less disagreeable, depending on the position they occupy and the purpose to which the resulting bar steel is applied.

This possible lack of homogeneity in crucible steels made by modern methods has very little, if anything, to do with the question frequently asked, *i. e.* whether the ordinary carbon tool steel now produced is as good in all respects as that made, say forty, or fifty years ago; but it has a good deal to do with certain kinds of defects in alloy steels, and may also be held accountable now and again for defective tools made from ordinary carbon steels.

The quality of tool steel refers generally to the absence of harmful impurities attained by selecting the purest raw materials and the virtues conferred by manipulating them in the way experience has shown to be best. But something more than chemical purity, *i. e.* relative freedom of the raw materials from sulphur and phosphorus, is thought to be essential, and that something, vaguely defined and spoken of as "body," is supposed to exist in a superlative degree in certain brands of Swedish bar iron.

Body in steel.

To invite discussion on the nature and occurrence of "body" in tool steel may be unpopular. But scientific investigation and teaching must be free in every direction, and if we desire to understand and explain current statements on the subject, rather than merely accept and repeat them, an unprejudiced inquiry is essential. Whether any new views arrived at will prove to be right or wrong, no one can say; but every one has the right to oppose views he believes to be erroneous so long as the instrument of opposition is not brute strength of

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less, and many kinds of material that used to be forged are now rolled. As a net result the work is finished more quickly and receives less personal care. This applies also to high-priced bars that were formerly almost nursed into the fittest possible condition into which a bar of tool steel can be brought.

Meanwhile, the notion persists that the quality of bar steel depends on the amount of "body" in the irons from which it is made, whereas it may depend mainly on the care and skill put into the treatment of it—quality and "body" being by no means synonymous terms.

When pieces are broken from the opposite ends of a bar of steel, it is sometimes found that one of the pieces has the kind of fracture the skilled warehouseman calls nice, *i. e.* it is fine in grain, curved in outline and not dry in appearance; whereas the fracture from the other end is coarse in grain and has the staring appearance of overheated steel. Both pieces having being part of the same bar must be credited with equal "body"; the one, however, if made into sates, boiler-makers' snaps, or other tools in which the properties of the steel were not greatly altered by reforging or other forms of heat treatment, would give satisfaction, the other would give just cause for complaint.

The author has seen tools by the barrowful wastefully broken, although made from high-priced crucible steels containing presumably much "body," and similar tools satisfactorily re-made from well-selected open-hearth steel. And all along the line of observation it will be found that bar steel, however much "body" it contains, may be spoiled in the process of manufacture and is then less reliable, as tool steel, than well-made steel of the cheaper sorts. From such experiences it may be concluded that "body" irons are not a complete criterion of the quality of the bar steel produced from them.

But when the expensive "body" irons are handled throughout in a superlative manner, are they not superior to the cheaper irons of like purity which have been handled equally well? Most steelmakers say they are

superior, and quote many years' experience in favour of their opinion; very few think otherwise. Having searched for evidence both experimentally and in other ways, with an hereditary bias in favour of the prevailing notion, the author finds no properties in "body" steels except those due to the chemical and physical properties of the raw material modified by skilful handling; and it is both gratifying and useful to find the tool steels thus brought into the same line of vision as other steels.

But if traditional irons said to contain "body" may be neglected, the traditional skill and care of the old helve-hammer tilters might advantageously be preserved. Less "body" would be no great loss, but more brains put into supervision and rejections for neglectful workmanship would be a great gain.

To sum up, it may be said that raw materials used for the manufacture of tool steel should be as free as possible from harmful impurities, which mean generally sulphur and phosphorus. The relative harmfulness of these two elements cannot be precisely stated, and their possible effects must be judged according to circumstances in the light of the fact that phosphorus is in solution and generally more uniformly diffused throughout the steel, whereas sulphur occurs as small non-metallic particles of sulphide scattered more or less regularly in the steel; the harmful influence of sulphur when present in large amounts cannot be minimized by adding manganese, because only small amounts of manganese are usually admissible in tool steel. IMPURITIES.

The raw materials should not contain much silicon, as not much of it would be lost during the melting operation; and there may even be a gain bringing the total up to ·40 per cent. if graphite crucibles are used. Manganese up to about one per cent. may be present in the scrap forming part of the charge; 40 to 60 per cent. of it will slag off and tend to deepen the wash line on the pot at the surface of the fluid metal. A suitable quantity of scrap steel, rich in silicon and manganese, is a very helpful addition to charges of certain irons, which have

been over-oxidized in the refining operation and are hence apt to be "wild."

In addition to the control exercised by chemical analysis and common sense, it is far more important than is generally recognized to have each constituent of the charge in such form as is fusible at the furnace temperature. "I like to see the charge go down in the pot altogether," said a very observant steelmaker, and this provision, coupled with the use of materials of appropriate composition, goes a long way towards the making of fluid steel fit to be poured into an ingot mould. The actual casting of the ingot is another matter.

III

PROPERTIES OF INGOTS

HIGH-GRADE crucible steel was formerly the purest form of cast steel known. It was rivalled in chemical purity only by Swedish (bessemer and open-hearth) steel; it is now equalled, if not surpassed, in that respect by certain electric furnace steels. But in general reliability for toolmaking purposes, crucible steel is unequalled; the reason being that steel is not completely made until it has been cast, and no method of casting ingots is so nearly perfect as that practised by the crucible steel melter. Also, no form of ingot mould is so easy to scrutinize as the one he uses, and no form of ingot is so carefully examined and prepared for the subsequent operations. Much of the virtue ascribed to Swedish steels is due to the excellent way in which they are usually cast; much of the disappointment attending the use of electric furnace tool steels is due also to the way in which they are usually cast. The properties of ingots as modified by casting temperature, method of casting, shape of ingot mould, etc., is the subject of this chapter, and one of which the user of tool steel should have some knowledge if he would understand the causes from which a few of his troubles arise.

(A) CRYSTALLINE STRUCTURE AND ITS EFFECTS

When steel or any other crystalline substance is cast into a mould the freezing commences from the inner surfaces of the mould, supposing the substance is quite fluid to begin with. Assuming the mould to be made from cast iron and its cross-section a square, then freezing in any plane occurs more rapidly at the corners than elsewhere; and the crystals lying in and about the corners, in

consequence of the rapid cooling, are comparatively small ones. Crystals grow also from the sides of the mould, but as their growth sideways is hindered by the adjacent crystals and their growth forward into the fluid mass is less restrained, they become long and narrow in shape. The crystals growing from any one side of the ingot mould, presuming the interior mass remains fluid, meet crystals growing from the adjacent sides, and a boundary to the cooling effect of each side of the mould is visible

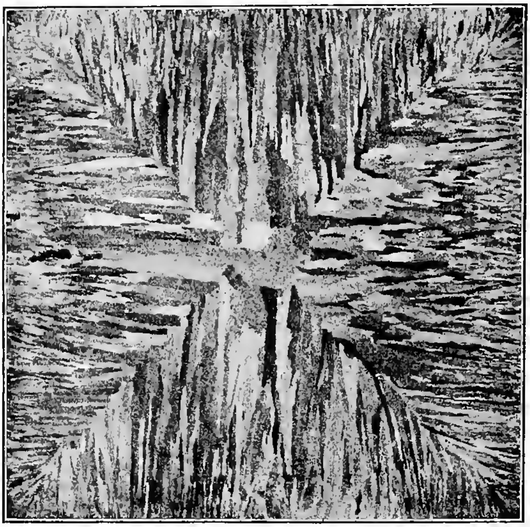


FIG. 8.—Transverse section of crucible steel ingot.

on a polished and etched specimen, or on a fractured surface, as junction lines lying diagonally on the square. These remarks are illustrated by Fig. 8, made from a section of a four-inch-square chromium steel ingot.

In the same way, from the bottom of the mould, which is assumed to be flat, crystals grow upwards until they meet those crystals growing from the sides of the lower part of the mould. It is easy to realize that crystals growing thus, from surfaces at right angles to each other, would meet obliquely on planes which outline the form of a four-sided pyramid. In the same way the cooling effect of the atmosphere on the free upper surface would

cause crystals of the same narrow kind to grow downwards until they also terminated on the surface of a four-sided pyramid, assuming, of course, that the fluid material froze quietly and was not disturbed at the upper end by shrinkage cavities or segregation effects. These considerations enable us to make a sketch diagram illustrating the arrangement of crystals as seen in a longitudinal section cut through the axis parallel to a side of the ingot (Fig. 9A); in a cross-section cut at right angles to the axis of the ingot near the bottom (Fig. 9B);

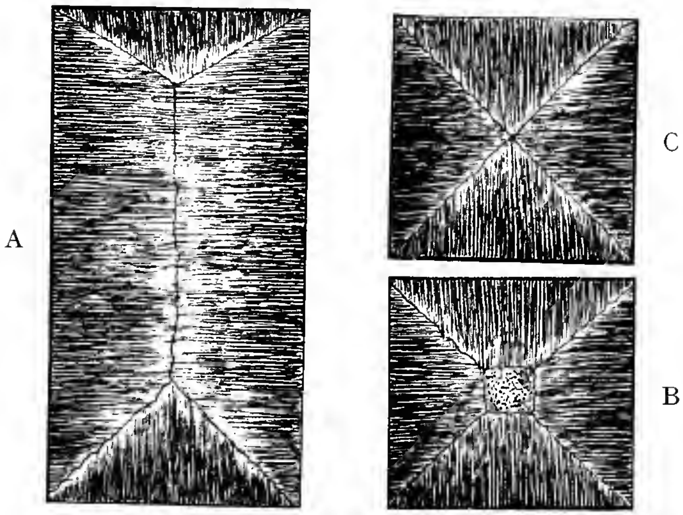


FIG. 9.—Sketch diagram to illustrate arrangement of crystals in ingot.

and in a similar section cut nearer the middle of the ingot (Fig. 9C). The height of the pyramid at the foot of the ingot is a measure of the cooling effect of the base as compared with the sides of the mould, and this can be advantageously modified by altering its shape or interposing non-conducting material.

PLANES OF WEAKNESS.

The diagonal lines in Figs. 8 and 9 are lines of extreme weakness; partly because they are lines of contact between crystals growing in different directions to each other, and partly because they are coincident with the intersection of plane surfaces in the ingot, which at successive moments were the last to solidify. Consequently

the diagonal planes are rich in segregates and non-metallic impurities (if such, as in steel, can possibly form), they are likely to be occupied by elongated gas cavities, and are also in the position where small cavities caused by contraction stresses would form. The influence of segregate plus shrinkage cavities would account for a great deal of the observed weakness along these diagonal planes, and it is not possible to determine, apart from this influence, how much of the observed weakness is due only to the crystalline arrangement.

The orderly arrangement of the elongated crystals enables the ingot to be split easily at right angles to either face of the ingot mould and either parallel to or at right angles to the axis of the ingot. In addition to this weakness there are others, more serious in their effects on material which has to be rolled or forged, that depend on the shape of the mould. In a square ingot they originate at the corners of the mould and divide the ingot into four triangular prisms whose bases are the sides of a quadrilateral pyramid which grows from the bottom of the mould. In a round ingot the crystals growing from the bottom of the mould are formed into a cone, and in an octagon ingot they form an eight-sided pyramid. In each case the base pyramid is longer or shorter, depending on the cooling effect of the bottom in relation to the cooling effect of the sides; but generally the base exerts its full effect because it remains throughout in direct contact with the freezing ingot, whereas the sides of the ingot, soon after solidifying, leave the mould and are thereby partially insulated from its cooling effect by a gaseous envelope.

GROWTH OF CRYSTALS.

The growth of elongated crystals originating at the surface of an ingot mould depends on circumstances which appear to be somewhat contradictory, *i. e.* they are favoured sometimes by slow cooling and sometimes by rapid cooling. So long as the fluid in the interior of the partly solidified ingot remains quite liquid, the crystals already growing from the sides of the mould increase in length, as the temperature of the liquid about their extreme ends falls to freezing point. The act of freezing

liberates heat which is either stored up in the fluid, or dissipated, *via* the solid crystals, through the sides of the ingot mould. When the crystals are bad conductors of heat the cooling is necessarily slow whatever the properties of the ingot mould may be, and the fluid in the centre of the ingot remains clear almost to the last drop. Under these circumstances quick cooling is impossible (except by stirring or otherwise hastening the setting by mechanical means), and the crystals grow with their greatest length lying between the sides and centre of the mould.

But, if the crystals themselves are good conductors of heat, then the latent heat liberated as they form, and also the sensible heat from the fluid interior, are rapidly dissipated through them. In this way the temperature of a large volume of fluid may reach its freezing point in many places simultaneously before the crystals growing from the sides can extend to the centre, and thus the interior of the ingot would consist of crystals which had grown from independent centres and were developed equally in all directions.

Of crystallizable substances, therefore, which are quite liquid when cast, those that are poor conductors of heat will form crystals of the same kind from the surface inwards if allowed to cool undisturbed. Steel, on the other hand, being a good conductor of heat, will form crystals of the same kind from surface to centre of the ingot only if the cooling takes place very quickly or very slowly. In the former case the crystals grow and extend themselves rapidly into the clear liquid as its temperature falls to freezing point; the results being narrow crystals like those seen in Fig. 8. In the latter case, however, the cooling is so slow that the temperature of the fluid mass, owing to its high thermal conductivity, is practically uniform throughout, and a crystal is therefore as likely to start growing in one place as another, the result being irregular and approximately equiaxial crystals like those seen in Fig. 1.

There exists obviously a great number of instances where both kinds of crystals occur in the same ingot, as

seen in Fig. 10, the exterior crystals being needle-shaped and the interior equiaxial.

(B) SHRINKAGE AND CONTRACTION CAVITIES

If we imagine an ingot mould filled with fluid material that could be cooled with perfect uniformity down to its freezing point, we should find that the level of the fluid would gradually sink as the fluid cooled and shrank. If at this point the fluid were to solidify instantaneously

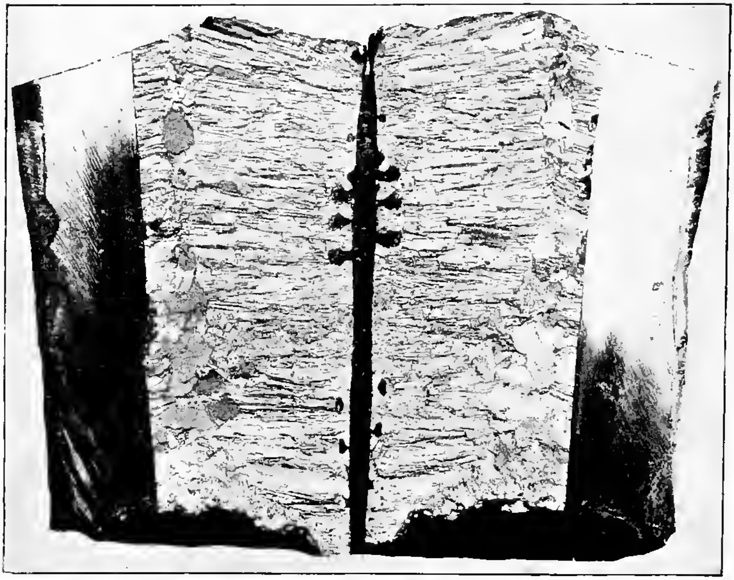


FIG. 10.—"Needle" and "equiaxial" crystals in same ingot.

without change of volume we should have a solid ingot. But steel does not behave in this manner, and cavities due both to shrinkage of the fluid and contraction of the solid material exert a great influence on the economic production of ingots.

The main shrinkage cavity of an ingot which exists about the axis, and generally opens to the air, is known as "pipe" or "piping." It is due to the gradual shrinkage during solidification of the metal in successive layers towards the inside.

How ingots freeze.

A steel ingot just cast consists of a thin shell of solid metal with a fluid interior. The outside length of the ingot has been fixed by the thin solid envelope extending downwards from the highest level of the molten steel in the mould. After a very short time the solid envelope thickens, say, by a millimetre, but before that occurs the fluid steel has cooled and, owing to shrinkage, stands now at a lower level. This has been represented in Fig. 11 by a step down between the first and second millimetre in thickness of the freezing envelope. This process may be regarded as repeating itself in successive and distinct stages as long as any fluid steel remains in the interior of the ingot, and as a result the central cavity or pipe would be as represented in Fig. 11. As a matter of fact, Fig. 11 does represent pipes in ingots cast in moulds having parallel sides. It differs from an actual pipe only because the thickening of the solid envelope is a continuous process and not an intermittent one; and also because the contraction of the solid envelope and the cooling effect of the atmosphere on the upper surface of the ingot must also be taken into account.

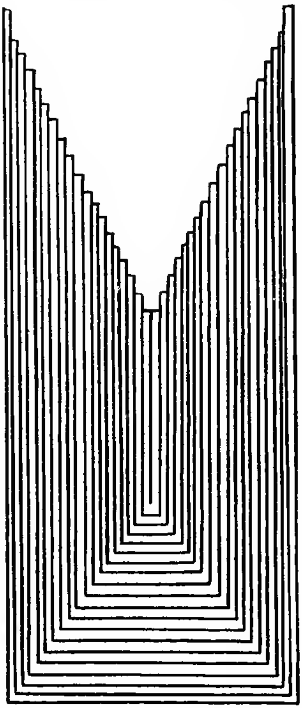


FIG. 11.—To illustrate the freezing of ingot with parallel sides.

That steel freezes by the uniform thickening of the shell first formed is a fact known to most furnacemen, who have opportunities now and again of seeing ingots broken up that have been upset or otherwise accidentally and completely bled. By way of illustration we reproduce Fig. 12, representing a crucible steel ingot that was intentionally inverted; and Fig. 13, representing a much larger ingot from a series prepared by Talbot (*Journ.*

Iron and Steel Inst., 1913, i. 30). When freezing takes place in the fluid mass from independent centres the above conditions do not apply.

The influence exerted by the shape of ingot mould on the position and dimensions of the pipe is discussed

Fig. 12.—Crucible ingot inverted whilst partly fluid.

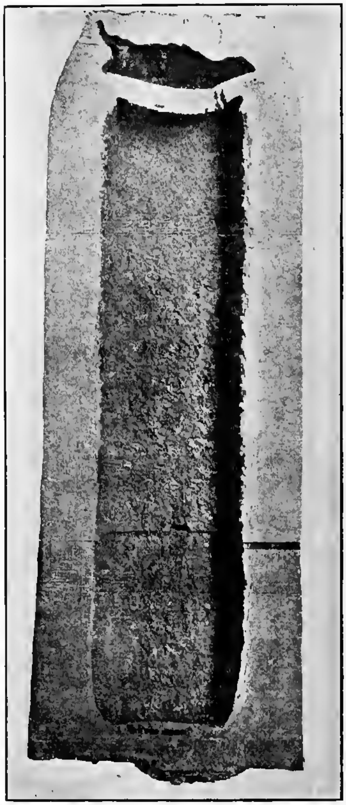


Fig. 13.—Bled ingot showing even thickness of solid shell.

later; but it is desirable at this stage to consider a feature exhibited by many ingots cast in straight-sided moulds as distinct from taper moulds used with either the narrow or wide end up.

Central cavities.

When sufficiently removed from the cooling influence of the closed bottom and the open top of an ingot mould, the freezing of any horizontal section of the fluid ingot may be regarded as due to loss of heat through the sides

of the mould. When the mould has the same cross-sectional dimensions from top to bottom, the crystals growing from the sides of the ingot in any one plane are likely to meet in the centre as soon as those growing in any other plane. On this condition being approximated a plane of the material is all but rigid; quite too

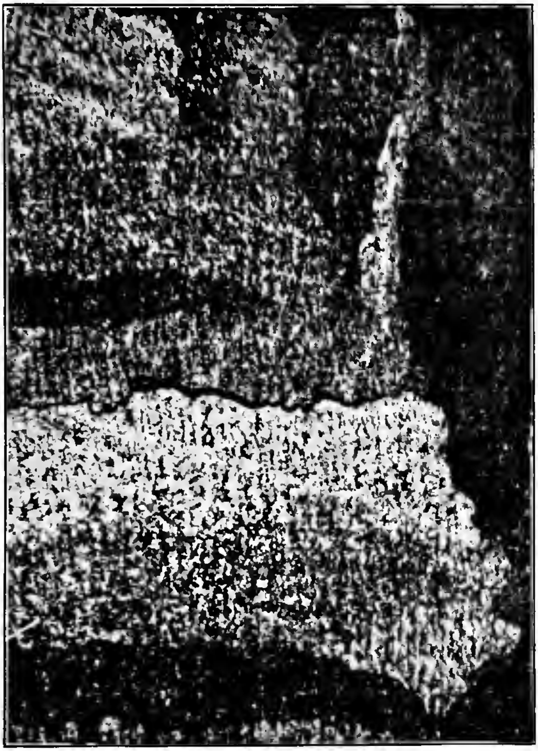


FIG. 14.—Crack between "needle" crystals in crucible ingot.

rigid at the centre to flow downwards, but requiring still to contract over its entire area. The material next to the ingot mould is coolest and most rigid, and if the unavoidable contraction cannot pull the flat outer surfaces inwards the assumed planes must split at the centre where the material, all but set, offers little resistance. The result is a small central cavity with no material above it fluid enough to flow downwards, and the net effect in an ingot of this kind is a number of small cavities, roughly

spherical in shape, lying in the axis of the ingot. For shrinkage or contraction cavities of this kind an increased length or breadth of feeder head is a doubtful remedy, as in actual practice such cavities occur always in small crucible ingots cast into straight-sided moulds and fed by means of a hot dozzle.

INTER-CRYSTAL-LINE CRACKS.

But, in addition to cavities that are obvious to the naked eye, it is not unusual in steel ingots to find cracks running between crystals at right angles to the surface through which the ingot has cooled. These cracks are discoverable by direct microscopic observation as in Fig. 14, which is an enlargement of part of Fig. 8; or indirectly by making use of a corrosion effect.

In some cases cracks are revealed in large numbers by immersing a cross-sectional disc cut from an ingot in a ten per cent. solution of hydrochloric acid. The acid attacks the metal most vigorously along the edges of an existing crack and eventually the crack widens into a visible cavity. Cavities of a similar kind originating from segregated areas may also be developed by extended pickling; but there are decisive means of distinguishing one kind from the other, such as the direction of the cavity in relation to the length of the crystal, and confusion is not likely to arise if careful observation be made of the scattered distribution of the former compared with the occurrence in groups of the latter.

If the material in which the cracks occur is not weldable then it is also not forgable, but will crumble under the hammer. This explains why certain alloy steel ingots may not be forged, whereas others of the same composition, but melted and cast under different conditions, forge quite well. The behaviour of 25 per cent. nickel steel may be referred to in illustration of this statement; if low in manganese it breaks up on forging very readily when cast hot (as it frequently is), whilst when cast at a much lower temperature it withstands an almost unlimited amount of deformation under the hammer.

(C) CASTING TEMPERATURES

When a crucible steel ingot breaks with a needle-like fracture resembling Fig. 9 and the outer parts of the ingot represented in Fig. 10, it is said to be "scorched," and scorching is said to be due to the molten steel having "had too much fire." A furnaceman does not generally commit himself by saying whether the steel has been for too long a time in the furnace or at too high a temperature. He may not know; but he does know a scorched ingot can be broken across with remarkable ease and that he will very likely get into trouble if he makes many such ingots. Badly scorched ingots used formerly to be broken up and re-melted; under the present method of "topping" ingots the extent of the scorching is not so fully exposed and many suspects are sent to the forge and mill.

Scorched ingots are objectionable only on account of their fragility due to arrangement of the crystals in definite directions and the extended contraction cavities which may arise. This is, of course, a serious objection, because unless the scorched ingot, after re-heating, is very carefully and, to begin with, very gently forged, the weakness between the well-developed crystals will cause cracks to form on the edges and corners of the forged bar. But, apart from obvious defects like these, the steel is neither better nor worse in quality for having shown the scorched appearance in the ingot. SCORCHED INGOTS.

However intimate one's knowledge of a fluid steel may be, it is not easy to say beforehand whether an ingot produced from it will be scorched or not. The determining conditions are casting temperature and speed, material, mass of the ingot mould, and its cross-sectional area. Fluid steel cast into a small mould may produce an ingot scorched to the centre, whereas the same steel cast into a similar but larger mould may show little or no scorch.

The general conditions affecting the appearance of scorch have been discussed on p. 23. They apply not only to steel but also to most other metals and alloys, and though they may not be summarized exactly in brief

sentences, it may be said that if an ingot is made large enough it will not be scorched, whatever the casting temperature may be; also if it be cooled slowly enough it will not be scorched, whatever the size of the ingot or the casting temperature may be. And consequently, though a high casting temperature may be favourable to a scorched appearance, it may, if very high, act unfavourably by warming up the mould and thereby delaying the rate of cooling.

Fig. 15.—Base pyramid in 8-cwt. steel ingot.

If an ingot cast at high temperature is exposed, during the act of cooling, to such forces as resist its contraction, it can be pulled to pieces more or less completely along the diagonal planes of weakness referred to on p. 21 and indicated in Fig. 9. An interesting example of this fact is reproduced in Fig. 15, which represents the separated basal pyramid in a square ingot (of steel) weighing about eight hundredweights.

Three-inch-square ingots which are badly scorched are so tender that sometimes they break during the loading into or unloading from a cart, whereas an ingot of the same composition cast "cold" is very difficult to break with a sledge hammer. Between these two extremes lie ingots which can be broken more or less easily for reasons due to, but not generally associated with, the temperature at which the respective ingots were cast.

The strongest possible ingot is the one cast when the fluid metal is just on the point of freezing and has begun

to crystallize on the surface. Such ingots when fractured do not show a needle-like crystalline structure, and their outer surfaces are slightly uneven.

Low casting-temperatures.

It is not difficult to understand the characteristic properties of both the inside and outside of "cold-cast" ingots. First as to the outside—as the metal per assumption has already reached its freezing temperature it solidifies immediately on contact with the bottom and sides of the mould. It freezes also over the free upper surface into a crust of slender crystals, and as the metal is poured the liquid level and the solid crust rise together, the latter gradually increasing in thickness. But the crystalline crust has solidified in a piece with the sides of the ingot, and as the fluid metal rises in the mould it pushes the crust upwards most effectively where it is least restrained, *i. e.* near its centre. The crust, therefore, becomes increasingly convex until, broken by upward pressure of the fluid metal, a new surface is formed. In the act of forming the new surface the fluid metal strikes the mould and is frozen before it can fill up the lowest part of the convexity; hence the surface of the stripped ingot is a series of rings where it has been in contact with the mould and a series of depressions lying alternately between them where it has not been in contact with the mould (see Fig. 16).

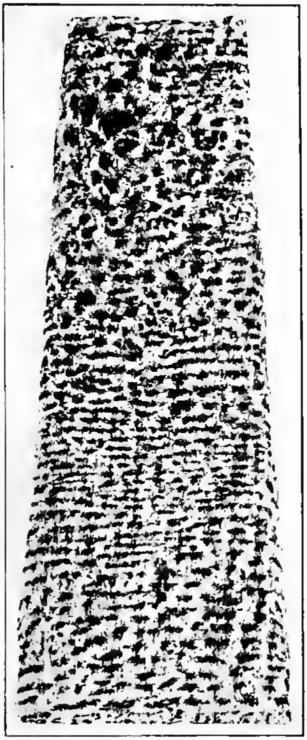


Fig. 16.—Surface of "cold-cast" ingot.

Pieces of the broken crystalline crust may wash into the fluid metal and form independent centres of crystallization. This may also lead to blowholes in steel owing

to a liberation of gas promoted by the oxidized surfaces of the solid metal occlusions; or to irregular lines of weakness which weld but incompletely in the subsequent forging. It is, therefore, not always advisable to strengthen the ingot by "cold casting," and with certain kinds of alloy steels it would be most unwise to attempt to do so.

The internal structure of a "cold cast" ingot is unlike that of a "hot cast" ingot, because in the former case the centres of crystallization are dispersed throughout the entire ingot instead of being confined to the inner surfaces of the mould or the solid steel already adjacent to it. The crystals, therefore, do not grow in planes, as it were, but in all directions, forming roughly-spherical clusters. These clusters of solid crystals are heavier than the fluid metal and sink towards the bottom of the ingot; if, therefore, any well-defined acicular crystals grow into prominence, they are likely to be found in the upper part of the ingot.

FIG. 17.—Crystals of antimony floated to top end of ingot.

We have said previously that an ingot freezes by a gradual and uniform thickening of its solid walls in planes approximately parallel to the inner surfaces of the ingot mould. This statement applies, however, only whilst the conditions are such that the interior of the ingot is quite fluid. If free crystals form in the liquid metal independent of the cooling effect of the mould, they will rise, as in antimony-lead alloys (see Fig. 17), if they are lighter, or sink, as in steel, if they are heavier than the mother liquor. In the latter case the base of the ingot will be thicker, at any moment during

solidification, than can be accounted for by direct cooling effects in those positions.

The formation of free crystals in the fluid portion of cooling metal influences greatly the properties of an ingot. It adds considerably to its mechanical strength by interfering with the growth of elongated crystals at right angles to the sides of the ingot mould, *i. e.* by suppressing the scorched appearance; this is apparent in small crucible ingots by the greater effort required to "top" them. In large ingots the formation of free crystals which sink downwards increases the difference in carbon content between the top and bottom portions of the ingot. In very large ingots this difference is so serious that in order to obviate it two casting ladles are used, the one emptied first containing steel higher in carbon than the second.

HIGH CASTING-TEMPERATURES.

The general effects of a high casting temperature are harmful, and the increased smoothness of the outer skin of an ingot which may possibly be thus obtained is a delusive advantage. An ingot is raw material for the production of forgings, and has usually to be re-heated before it reaches the hammer or the rolling mill. It is advisable, therefore, that it should withstand the re-heating without cracking or bursting either internally or externally. A high casting temperature increases the amount of total shrinkage and lengthens, therefore, or broadens the pipe; this defect could be remedied by scrapping more of the ingot or feeding the shrinkage with sufficiently fluid metal. But a high casting temperature increases also the number and dimensions of contraction cavities and cracks, and adds to the weakness of the ingot along the planes which lie between the corners and its centre. The defects are the more serious because they are mainly unsuspected until the forging has been partly worked, maybe machined, and great expense put into it.

(D) THE SHAPE OF THE INGOT MOULDS

A split ingot mould may have parallel sides, but the inner walls of a solid mould must be tapered, otherwise there

would be endless trouble in the stripping operation. Most ordinary ingots are cast with the narrow end of the taper mould upwards, as this enables the mould to be lifted off whilst the interior of the ingot is still fluid. This practice is economical both as to ingot moulds, which last longer because they are not made needlessly hot, and in the further costs of working the ingots if the same are charged hot into re-heating furnaces. The following remarks

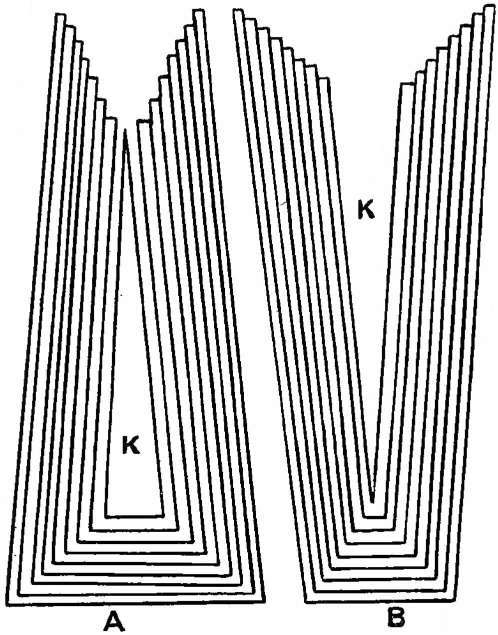


FIG. 18.—How steel freezes in taper moulds.

apply only to such ingots as are allowed to go cold under normal conditions, and are made solely in the interest of sound ingots without any regard to particular workshop conditions, big outputs and apparent economies.

TAPER MOULDS.

Assuming that a taper ingot mould with the narrow end upwards is full of fluid metal at a uniform temperature, the act of setting, as before, may be represented by a series of equidistant lines drawn on a longitudinal section of the mould parallel to its inner surface, as in Fig. 18*a*; each line being made shorter than its predecessor

to account for the continuous shrinkage. The point at which a pair of these lines meet within the mould may be taken to indicate that in the horizontal plane passing through it the metal has solidified completely. The cavity above the point of intersection is a pipe pure and simple and may be distinguished as "primary pipe." But there still remains a triangle marked K which, according to our assumption, contains fluid metal and is hermetically sealed. This fluid in due course will also shrink and freeze and contract, but there is no possibility of the cavities thus formed being fed, and consequently there arises a more or less discontinuous extension of the primary pipe which may be called "secondary pipe."

On representing in the same manner the freezing of metal cast into a taper mould with the wide end up, but with shorter steps down because the shrinking fluid is falling from a wider into a narrower part, we arrive at Fig. 18*b*; there also the lines intersect and represent similarly that the material lying at the point of intersection (and below it) has become solid. There is also a triangular residue of fluid metal, but in this case the triangle is inverted and the metal within it will freeze earliest at the lowest point, any shrinkage being meanwhile fed from above, and leave finally a single shrinkage cavity about the axis and at the upper end of the ingot. It is not possible in this kind of ingot to have a "secondary pipe."

The assumptions on which Fig. 18 is based take into account neither the speed at which the ingot is cast nor the cooling effect of the air on its upper surface. Also ingots are not made by filling moulds at the greatest possible speed, or, when they are, the ingots are inferior ones.

The cooling effect of the air forms a cover of greater or less thickness over the upper end of the pipe. In large ingots the thickness of this cover may be several inches, in small ingots it may not persist at all; but in either case the atmospheric cooling thickens also the metal about the upper part of the pipe. If, however, the influence of these variations be added to the hypo-

thetical case represented by Fig. 18, it will not be modified out of all recognition, as may be seen by comparing the assumed forms with those of two actual steel ingots reproduced in Fig. 19.

IN-VERTED MOULDS.

Nothing can be devised to prevent the shrinkage of steel as it passes from the liquid to the solid state, and the only means of providing against the inconvenience of it is to arrange for liquid metal to be kept at a higher

FIG. 19.—Small steel ingots cast in taper moulds.

level ready and able to flow into what otherwise would be a shrinkage cavity. This means that an ingot should always solidify from the bottom upwards, which it does naturally when cast into a taper mould with the wide end up; or, in general terms, the metal in any plane must solidify earlier than the metal in a higher plane if shrinkage cavities are to be avoided.

A fluid ingot cast with the wide end up shortens less rapidly than a similar one cast with the narrow end up, and it is, therefore, more likely in the former case that

the upper crust of frozen metal will resist the pressure of the atmosphere when the fluid underneath ceases to support it. This to some (not very great) extent will help to keep the upper and interior part of the steel fluid; it is more valuable, however, because it may prevent oxidation of the interior of the pipe and thus facilitate its welding during the later forging or rolling operation. It may also be observed that the pipe in the one case takes the form of a long, pointed cavity, and in the other a short cavity with rounded end (Fig. 19). Apart from the relative volume of material thus made unsound and likely to be scrapped, the former, occurring in ingots cast with the narrow end up, is more likely to cause ingots to "clink" in the re-heating furnace. These are points of minor importance in themselves, but experience shows that they lead sometimes to grave consequences, and it is therefore worth while to note that in these minor respects also the reliability of ingots is improved by casting them with the wide end up.

The pipe in a series of ingots made in moulds of a gradually decreasing taper undergoes a continuous change, as the taper decreases until the sides of the mould become parallel; after that a very slight widening of the mould upwards alters the character of the pipe altogether, and it becomes shorter and more rounded at its lower end, and secondary pipe occurs only under abnormal circumstances. When the sides of the mould are parallel the ingots exhibit the special feature mentioned on p. 27. There are also other effects arising from the use of straight-sided moulds which may be glanced at for the sake of their bearing on the production and properties of tool steels.

STRAIGHT MOULDS.

Until twenty or thirty years ago all crucible steel ingots were cast into straight-sided moulds, which were in halves and held together by rings and wedges. The extent to which the primary pipe extended in the smaller of such ingots was very well known. Every melter was aware that a well-piped ingot was practically free from blow-holes, that the pipe was larger when the metal was cast hot than when it was cast cold, and that a hard

steel piped more than a mild one. Ingots are still sometimes cast into moulds with parallel sides, but they are dozzled, and it is generally believed that the ingots so produced are quite sound. For some distance below the dozzled head they certainly are, but in the lower part of the ingot they are generally not sound. Out of six ingots made by different melters in two factories not

FIG. 20.—Cavities below dozzle in crucible ingots.

one, on splitting them longitudinally, was found to be free from axial cavities. After what has been said on p. 26, the cause of such unsoundness is not far to seek, and a photographic reproduction, Fig. 20, of two of the ingots may be left to speak for themselves whilst we consider defects in forged or rolled bars arising from them.

DANGEROUS CAVITIES. The disadvantage of a shrinkage cavity whose surface has been oxidized by exposure to the atmosphere is

recognized, no matter in whatever kind of steel it may occur; but it is widely believed that other kinds of cavities, say those represented in Fig. 20, will weld up on forging without the steel being any the worse. Such a view is not quite in harmony with actual experience, and it may be said that the question is not and cannot

Fig. 21.—Blisters formed on thin sheets during hot rolling.

be quite settled, as has been inferred, by boring holes into the ingots and cogged bars and then, after sealing hermetically, observing their behaviour on forging.

A hole made with a drill is smooth and perfectly clean. The interior of an unoxidized shrinkage cavity is uneven, and its walls may be lined with small crystallites, which make sharp angles with each other and form very favourable starting places for internal clinks when the ingot is re-heated too rashly. The surfaces of such cavities are

also not always clean; sulphide segregations may collect about them and one may sometimes find a fine coating of alumina which has been floated there on the decreasing mass of mother liquor and left high and dry as the last of the fluid falls to a lower level. It appears to be on this account that blisters raised on thin sheets during hot rolling (see Fig. 21) are occasionally found to be coated on their inner surfaces by a layer of alumina of a pale yellow colour. This also is sometimes responsible for the lamination of saws and other articles either during stamping or the subsequent hardening operation.

The central and unoxidized shrinkage cavities seen in Fig. 20 were at one time, during the progress of setting, filled with liquid steel which fed the crystallites of purer metal growing from the walls of the cavity. But whilst the fluid metal moved downwards the crystallites remained, and when the ingot becomes a billet or bar, that part of it formed from the free-standing crystallites is purer, *i. e.* contains less carbon and other segregating elements, than the surrounding material. This kind of defect (*i. e.* defect in bars destined for chisels, drills, rifle barrels, etc.) is most clearly visible to the naked eye in the fracture of steels containing between ·90 and 1·1 per cent. carbon, but can also be detected in lower or higher carbon steels on polished and etched surfaces. The position of a soft centre in a steel bar is the same as that of a hard centre, and the one may occur not far behind the other. Fig. 22 represents part of a bar which has been split longitudinally in order to disclose the soft centre.

The harder the steel the more important it is that the ingot should be free from these axial cavities. And that not only because the danger of clinking is greater and the chances of welding up the cavities are less, but because the harder material at forging or rolling temperatures is less ductile, and under distortion the cavities may actually extend. This observation is verified notably by the behaviour of high-speed steel, and on that account ingots of high-speed steel ought always to be cast in taper moulds with the wide end up. Neglect

of this precaution is one of the contributory causes to which the well-known splitting along their length of high-speed steel tools may be ascribed.

CATCHED INGOTS

The taper mould is not generally used for ingots whose wider end is less than four inches across, the reason being that, with the usual taper, the narrower and lower end

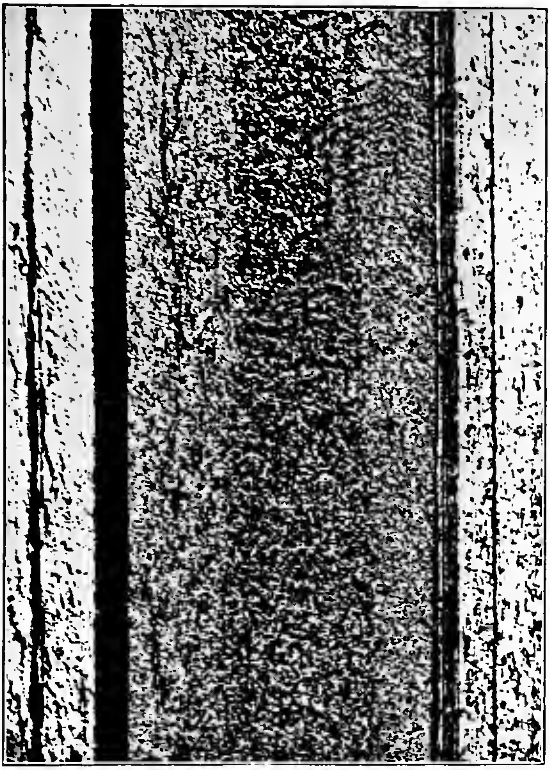


FIG. 22.—Soft centre arising from axial cavity in small ingot.

is too small to be struck directly by the molten stream without fear of its having previously impinged on the side of the mould. When a stream of molten steel strikes the side of the mould and part adheres thereto, the resulting ingot is said to be "catched." A catched ingot is objectionable because its surface is scarred, which may lead either to a lamination, akin to a lap, or a roak on the surface of the bar forged from it. On the surface of very hard steel, notably on self-hard steel

ingots, a " catch " may lead to deep transverse cracks in the forged bars.

That part of the fluid steel which strikes the side of the ingot mould and adheres to it is solidified and comparatively cold before the steel rising in the mould reaches up to and covers it. The cold strip of steel then adheres and becomes part of the ingot, and may be regarded as an inlaid strip of metal whose inner surface is more or less attached to the ingot. The strip, however, never remelts and its temperature does not become equal to the temperature of that part of the ingot in which it lies. As, therefore, the ingot shortens in length by contraction, the strip, unless it contracted at the same rate, which owing to variation in temperature it does not, will locally resist the contraction, and small cracks are thus induced to form. What happens is really a pull on a small scale, and the hardly discernible cracks on the ingots develop into obvious cracks on the bars forged from them.

It may also be observed that the metal immediately beneath an adhering " catch " is spongy. The sponginess is caused by oxidation of the surface of the strip of steel before the metal rising in the mould covers it. The oxide film reacts with the carbon of the fluid metal as soon as the two come into contact, and small quantities of carbon monoxide or dioxide gases are liberated, just as though part of the ingot mould were rusted.

The taper of the mould acts favourably or otherwise according as the wide end is up or down, whether the cross-sectional outline of the ingot be square, octagon, or round. The round ingot only, leaving the flat ingot entirely out of account, calls for special comment.

ROUND INGOTS.

Amongst a number of reasons why ingots should be made round, special prominence has been given to the fact that the area of their surfaces is less in proportion to their weight than can possibly obtain in any other form of ingot. This can be an advantage only if the ingot has surface defects, and even then it is a doubtful advantage, as the area of two forgings in any comparative case will be the same, and therefore particular defects in the round ingot will spread out more than would an

identical surface defect on an octagon, square, or flat ingot. It is true that defects in hot round ingots can be gouged out more easily than similar defects on a flat surface; also that the first deformation of a round ingot under a hammer or press causes a good deal of scale to loosen and fall off, thus lessening the danger of re-heating scale being hammered into the surface; the combined advantage is, at any rate, not a great one, and is offset by some disadvantage.

Round ingots are apt to crack both internally and externally. The suggestion that external cracks are due to expansion of the fluid steel as it solidifies is not supported either by actual observation or reasonable inference. Steel does not expand on solidifying, otherwise there would be no difficulty in casting ingots free from pipe, and cracked ingots of all shapes would be very common. Such cracks as may form on the outside of round ingots are frequently due to pressure exerted from the inside long after the ingot has become solid, and during the time when the main body of it is passing through the critical thermal changes; and such pressure, uniformly distributed, is greater per square inch of surface in round ingots than in those of any other shape.

Internal cracks are apt to occur in round ingots either after stripping or during re-heating, for the same reason that round bars of tool steel sometimes split up the centre on hardening and tempering. The outside of a large ingot is rigid long before the interior of it ceases to contract; if, therefore, the outside by added warmth (in the re-heating furnace) or by heat diffused from the inside, is caused to expand, there is an increase of tension at the centre which may pull it apart; and that occurs most easily, of course, through irregular and sharp-angled cavities.

The danger of cracking in round ingots increases with the hardness of the steel, and it is impracticable to make large round ingots of high-speed or air-hardening steel in chill moulds. The risk of cracking decreases with the diameter of the ingot, other things being equal, and it is, therefore, practicable to cast round ingots of air-hardening

steel up to six, eight and ten inches in diameter. On the Continent and (to a lesser extent) also in England high-class steel ingots are made in circular moulds, so that surface defects may be removed by turning before they are forged. This plan, properly carried out, seems to be an economical one.

SURFACE DEFECTS.

In certain kinds of sheet steel, steel for calico-printers' rollers, drop stampings, and in all intensive air-hardening steels, the condition of the surface of the ingot is responsible for many defects which spoils the forged article entirely. On this account the most carefully cast ingots may require chipping and, after cogging, may even be pickled in order to disclose further defects requiring to be ground or chipped out. In spite of so much trouble the final machining, or some subsequent operation, may disclose further faults which have originated from defects on or just below the surface of the ingot, *i. e.* one cannot be quite certain that every kind of surface defect has been got rid of. In some cases the security can be increased by leaving a large margin to be machined away; this, however, increases the cost both of material and labour and is still not an absolute safeguard.

Ingots made in circular moulds, after softening if necessary, can conveniently be turned. The process appears to be more satisfactory and actually cheaper than the usual method of pickling and chipping. If unavoidable defects of a serious kind occur it is economical to reject the material before much money has been spent on it. It is also undesirable, apart from any question of cost, that material should be found to contain defects after it has been delivered, as this gives rise to mistrust, claims for compensation, useless freights and various kinds of unproductive expenses.

There are also circumstances in which the ingot may or must be at once rolled to finished dimensions, and in those cases the importance of faultless surfaces cannot be overrated. Some continental firms making tool steel with electric furnace plants find it indispensable to cast round ingots and turn them, as it is not possible to cast ingots from a ladle with the care and success of the

competent melter, who pours the stream of molten steel over the lip of the pot when and how he pleases. Round ingots, therefore, of moderate size, say from two to ten cwt., are likely to be cast in larger rather than in smaller numbers.

IV

FRACTURES AND EXTERNAL APPEARANCES

THIS subject, considered in its logical order, should follow the study of forging and rolling operations. As, however, the toolmaker looks upon finished bars as raw material, he should be able, at the outset, to recognize those physical defects which are likely to lead to failure.

An ingot as cast is not always a perfectly continuous and homogeneous piece of material. Apart from segregation, which is rarely appreciable in small crucible steel ingots, there exists always the possibility of piping and blow-holes.

PIPE.

Pipe may be defined as the cavity formed by shrinkage as the molten metal passes gradually from the liquid to the solid state. Half a century ago, or less, the only remedy was to " top " the ingot after it had become cold : this operation is still performed, but the wastage is much less than formerly, because the upper part of the ingot mould is now lined with a white-hot fireclay sleeve—called a dozzle—which keeps the top portion of the metal molten, and free to move downwards as the shrinkage takes place.

HARD CENTRE.

In order further to increase the fluidity of the steel in the dozzle, a layer of fine charcoal is sometimes spread over the surface. The burning charcoal maintains the temperature, it is true, and also preserves the upper layer of metal in the fluid state longer than would otherwise be the case, but at the same time it carburizes it. See Fig. 23.

So long as the metal settles evenly in the dozzle only the upper layers, which are subsequently scrapped, become carburized, and no possible objection to the

practice can be raised. If, however, the carburized metal, owing to a badly heated dozzle or what not, should chance to run into the ingot itself, then the remedy in its ultimate consequences may be worse than the disease. A bar made from such an ingot would be much harder in the centre, along some portion of its

Fig. 23.—Effect of charcoal in dozzle.

length than elsewhere. The difference would be visible in the fractured surface and might become very pronounced if a section were polished and etched. A photograph of a chisel section with a hard centre is reproduced in Fig. 24. Such a bar of steel would make chisels apt to splinter at the cutting edge. Fig. 24*a* shows a longitudinal section through a cogged bar; made into tools, this might have caused much or little trouble according to the kind of tool into which it had been made. It

would, however, in nearly every case be detected and rejected in the steelmaker's warehouse.

BLOW-HOLES.

Blow-holes also, like pipes, were formerly more numerous in tool-steel ingots than they are to-day. On that account it was the practice to cog and weld all high-quality tool steel before it was tilted into bars. The

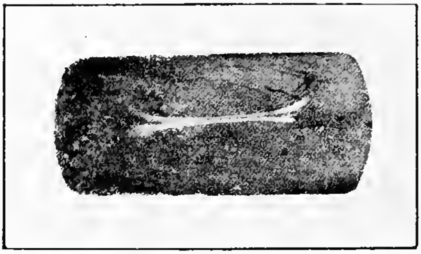


FIG. 24.—Hard centre in chisel steel.

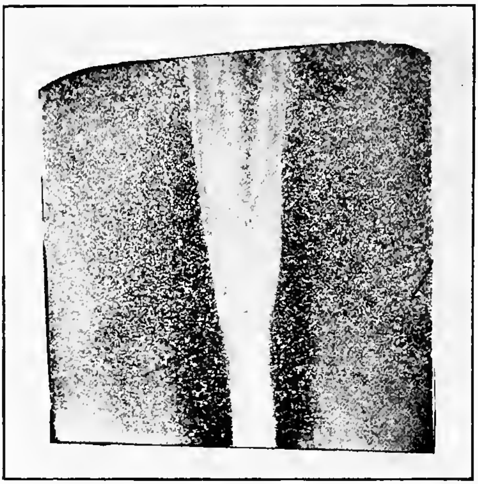


FIG. 24*a*.—Hard centre in cogged bar.

welding operation consisted in covering the hot bars with a fusible clay, bringing them to a yellow heat, and hammering them in order to produce sound bars free from surface defects.

Although blow-holes and surface defects are now less numerous in ingots, they have by no means entirely disappeared; and sometimes in an altered form they survive the more modern methods of production, escape the

pneumatic chipper, and even elude the wonderfully skilled eye of the warehouse examiner.

ROAKS.

The chief surface defects, appearing ultimately on bars as longer or shorter lines, which persist as a black or grey streak on being filed, are known as roaks. They are frequently caused by scale and slag filling up surface inequalities and getting hemmed in by the pressure of rolling or forging, as is shown by the magnified picture of roaks in Fig. 25.

FIG. 25.—Roaks in a cogged bar of mild steel. Transverse section. Magnified 10 diameters.

On being hardened, roaky bars frequently split right to the centre, especially if the steel hardens intensely. Chromium steel, for example, is especially subject to surface defects, and under some circumstances will invariably split on hardening unless the surface of the rolled bar has first been machined away.

CRUSHING.

The surfaces of internal defects, such as blow-holes, which have failed to weld up, always show some signs of polish caused by moving over each other. The surfaces are also flat and therefore easily distinguishable

from internal defects due to crushing in an insufficiently heated state between the rolls. Defects due to crushing arise less frequently in the mill than in the tool room, and will be more fully considered in a subsequent chapter.

LAPS. Laps are caused by a fash getting bent over on to the work and rolled in. It is easy to distinguish a lap from a roak, though either may be fatal. The former runs from its extreme edge obliquely into the bar; the direction of the latter is always towards the centre. When steel is forged into complex shapes and twisted about so that the centre of a billet gets displaced towards the surface of the forging, then a crack may be disclosed on machining which is not a lap, although it runs in an oblique direction into the steel. A lap originates on the surface of heated steel, and if examined under the microscope is found to enclose a layer of scale between two layers of ferrite which were originally decarburized surfaces.

REELING. The appearance of the surface of a bar, apart from any question of local defects, indicates more or less the temperature at which the bar left the finishing rolls. But a prejudice prevails amongst purchasers in favour of a smooth, highly polished blue surface, and many rolled bars therefore are reeled or otherwise worked at very low redness or even lower temperatures. This practice is more harmful than useful. The burnished surface pleases the eye and may lessen the tendency to rust, but it destroys a piece of evidence of real value anent the virtues of steel which are more than skin deep.

FRACTURES. The appearance of a fractured surface may be most misleading. It depends, in the first place, on the manner in which the fracture was made. The tensile test piece of a good unannealed steel casting pulled in the usual form of machine may be quite fibrous, but if a notched piece of the same steel be broken by a sharp blow it is always distinctly crystalline. It is therefore unwise to depend greatly on the evidence of fractures which have not been produced under known conditions. A piece notched with a three-cornered file or a hack-saw, or,

best of all, with a V-shaped cutter and broken sharply at one blow exposes a fairly reliable fracture.

JUDGING FRACTURES.

In material of the same kind, the fineness of the granular structure increases as the temperature at which the material has been finally rolled or hammered gets lower. This is an improvement down to a certain point, but may damage the material if it is carried too far : that is to say, below visible redness. The fracture should therefore be neither too fine nor too coarse. Unless the temper of the steel is very high the fracture should be curved and irregular—never straight or even jagged along straight lines.

The curved and torn appearance becomes more marked in softer steels. This important branch of the subject cannot be learned very thoroughly from books, but it is both easy and instructive to heat a few pieces from the same bar to varying temperatures—or prepare a single piece as described on p. 91—and, after cooling, study the fracture and other physical properties.

Amongst materials of different kinds the variations in fracture are of course greater, and only a foolish person would venture off-hand to fix finishing temperatures, grade the degree of hardness, and pass judgment. Still, however complex it may seem on paper, it is in actual practice possible to eliminate first one and then another variable, and finally develop a likely suspicion which can be confirmed or otherwise by simple tests.

NORMAL FRACTURES.

A fracture which may be considered normal for bar tool steel containing about ·90 per cent. carbon may be prepared from a piece which has been heated for half an hour to about 760° C., and allowed to cool in the air. Pieces of the same material, very much finer in fracture, have been finished at too low a temperature; pieces very much coarser in fracture at too high a temperature. The former, especially if it contains considerably over one per cent. of carbon, is apt to contain fine cracks quite invisible to the naked eye—or at best to be unduly strained. The latter is not sufficiently compact and strong, and will be found especially unsatisfactory if made into tools which have to withstand severe shock.

The shanks of boiler-makers' snaps made from such steel readily break in the groove and split from the head, to mention only one example of the many failures which may arise from this cause.

In order to give a quantitative value to these remarks, a bar one and a quarter inches round was rolled from a three-inch billet which had been heated to the correct temperature at one end and to a considerably higher temperature at the other end. Pieces broken from the respective ends of this bar had a very different appearance; one had a fine and the other a coarsely granular fracture. From these end pieces a rectangular bar 15 × 10 mm. was machined and notched. The notched

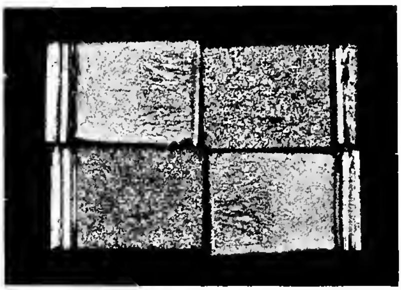


FIG. 26.—Coarse and fine fracture in same bar.

pieces were clamped in a vice, and struck by a pendulum hammer provided with an arrangement for measuring the force of the blow. In this way the energy required to break the finely granular material was found to be 60 ft.-lbs., and to break the coarsely granular material only 10 ft.-lbs. The fractures thus exposed are arranged corner-wise in Fig. 26.

DECARBURIZED SURFACES.

The skilled roller wisely insists on a "green" fire being kept in the grate in order to maintain as far as practicable a reducing atmosphere in the re-heating furnace. If this precaution is neglected, or if by any chance the ingots or billets are exposed at a high temperature to an oxidizing atmosphere, the surfaces become decarburized. The best known instance of this occurs in annealing steel castings (see Fig. 27), where the decarburized layer may

be one-eighth of an inch deep, and is rather an advantage than otherwise. On tool steel, however, a decarburized envelope of measurable thickness may cause a great deal of trouble in those uses where the bars are drawn to exact sizes; *e. g.* in the manufacture of hardened steel balls, or where the extreme surface must be made quite hard, as in the manufacture of files. If the thickness of the decarburized layer is excessive, it may justifiably be suspected that the bar has other defects, though they

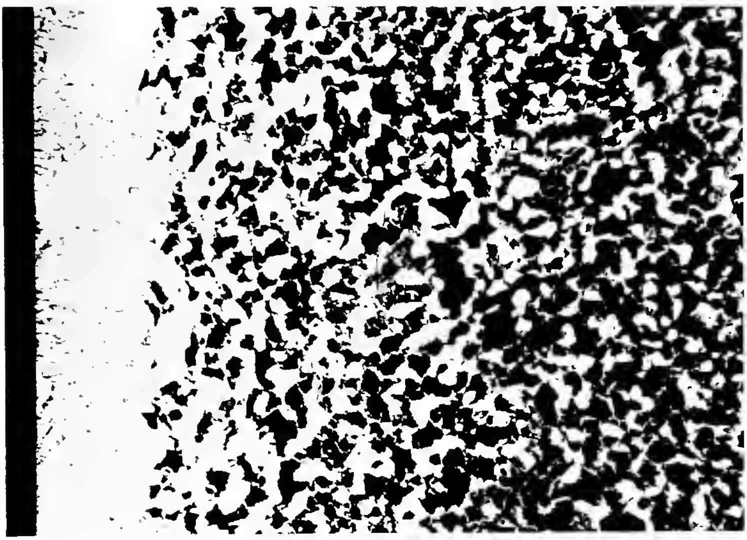


Fig. 27.—Decarburized layer on the surface of annealed steel.

may not be immediately obvious. Either the billet has been too long or at too high a temperature in the furnace, or both, and such irregularities are nearly as objectionable in the mill as they would be subsequently in the tool room.

When quenched out in the usual manner the decarburized surface does not harden, of course. Many complaints that steel will not harden may be traced to this cause by getting into the surface with the sharp corner of a file; the file ceases to bite as soon as metal of the normal composition is reached. If such a bar be broken the soft outer skin will bend back and form a

lip, which can be felt by passing the finger gently over the broken edge, and generally be seen with an ordinary pocket lens. In extreme cases a continuous lip may be formed something like the cupped fracture of a tensile test piece (see Fig. 28).

It is sometimes claimed that steel from which the

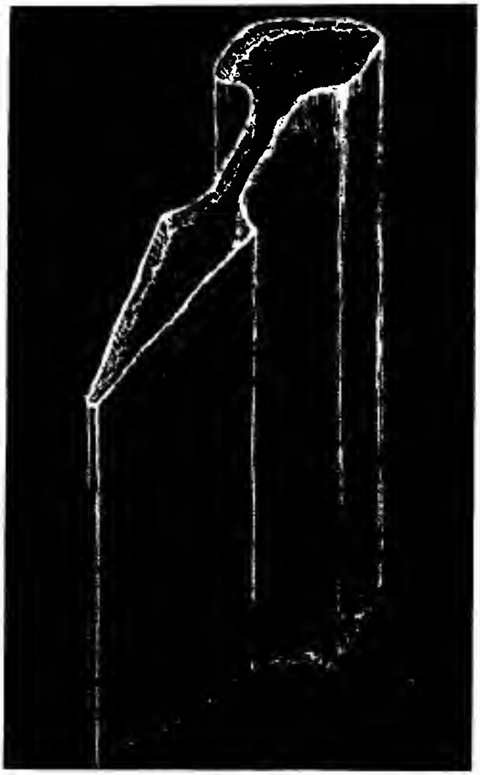


Fig. 28.—Fracture of steel tool whose surface has been decarburized.

rolled surface has been machined, is on that account more likely to crack than otherwise. This may occasionally be the case, because the decarburized outer surface resists the formation of incipient surface cracks. Generally, however, the converse is true, and there can be no question that it is safer to harden the machined bar except when surface decarburization is excessive; in these exceptional cases perhaps the best thing to do is not to use the bar at all.

V

FORGING TOOL STEEL

At this stage the toolmaker should recall what has been already said about coarse fractures, decarburized surfaces, laps, etc. It applies, perhaps, with greater force to the forging of tools than to the forging of bars, as the defects arise with equal ease and remedies are more difficult to find.

Two things are indispensable to good workmanship— CORRECT TEMPERATURE.

(1) A correct range of temperature, from beginning to end of the forging operation, which is suited to the kind of steel being handled.

A hard steel, for example, may not be heated so freely as a softer steel without danger of burning and making the steel more or less rotten, no matter what amount of work is subsequently put on it. But a piece of overheated steel, which if allowed to cool unworked would be very fragile, regains nearly if not quite all its good qualities if forged continuously from the high heat until it is dull red. It is obvious, therefore, that the temperature at the beginning of the operation should not be greater than will enable the forging to be completed at low redness. It should also on no account be greater than that at which experience has shown the material can be safely worked without producing split edges, nor should the finished operation under any circumstances leave the material with a fracture faintly resembling that of a dog biscuit. If the forging cannot be done within the above restrictions with one heating, then it should be heated twice; nor should a temperature of 1000° C. for hard material and 1100° C. for soft material be exceeded, no matter how much work has to be done on the object.

BLUE BRITTLENESS.

Some distance below a visibly red heat, that is at about 400° C., all kinds of tool steels are very sensitive to shock, and any mechanical operation, such as hammering, swaging, or flattening, has a great tendency to start very fine cracks, which are often no broader than the hundredth part of a hair's thickness, and cannot, therefore, be at all distinguished by the naked eye. This property is known technically as blue shortness, because it was supposed to occur in the neighbourhood of the temperature at which the blue tempering colour is formed. A curve connecting the tendency to fracture under impact blows with the temperature which has been worked out

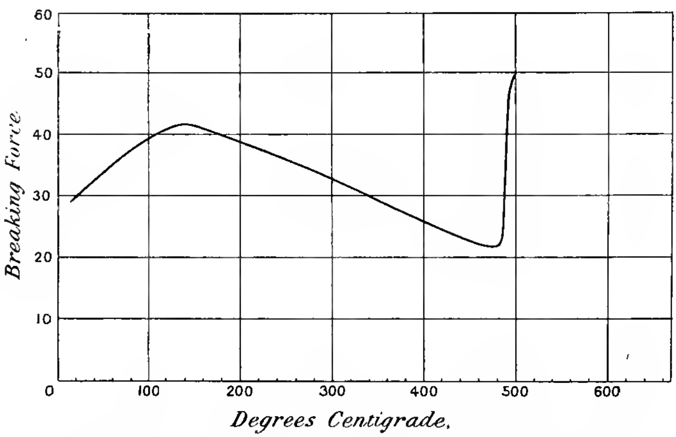


FIG. 29.—Curve representing fragility of tool steel at various temperatures.

for tool steel by Guillet & Revillon,[1] is reproduced in Fig. 29.

The instances in which defects can be traced to blue brittleness are numerous. In forging chisels, hatchets, plane-irons, or any other wedge-shaped tool, the smith, who likes to turn out a smart-looking job, will use the flattener long after the visible red colour has disappeared from the material. The sequel is seen in the hardening shop in the form of half-moon or thumb-nail cracks (see Fig. 30), until the smith learns that enough (forging)

[1] Fifth International Testing Congress, Copenhagen, 1909.

is better than too much. The characteristic thumb-nail crack can also arise from defective handling in the hardening shop, but with an example before us it is not, as we shall see, at all difficult to determine the prime cause.

CEMENTITE CRACKS.

The above considerations apply especially to very hard steel containing free cementite. The fine films of hard and brittle material provide an easy path along which the crack, once started, may travel. It is, therefore, necessary to prohibit the use of steel containing over one per cent. carbon, if in the subsequent rolling or forging operation any appreciable degree of cold working is unavoidable.

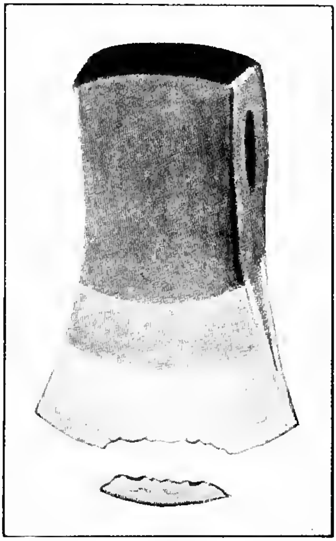


FIG. 30.—Thumb-nail cracks in hatchet.

The micro-photograph, Fig. 31, shows clearly how the position of the free cementite cell walls coincides with the path of the crack.

FORGING ROUNDS.

A round is the most difficult of all sections of hard steel to forge without starting defects, as it is also the most risky to harden. One well-known firm of steelmakers formerly cast all their crucible ingots in round moulds. The practice was justified by the presumption that the first blow of the hammer on the heated ingot would immediately loosen all the scale; and, further, that the round ingot presented a smaller scaling surface per unit of mass than any other shape. The toolsmith should not be allured by any such considerations into working round in preference to square sections. If a round bar needs to be tapered or reduced in diameter, it should first be gently flattened at the proper temperature and worked down to approximately the right size in the form of a square; then, and not before, it may be made into an octagon by knocking in the corners, and

finally into the desired round. If the bar is kept round from start to finish, it is highly probable that it would be split in the centre, or suffer from other defects which would lead to cracks in hardening.

The series of photographs in Fig. 32, illustrating the formation of split centres, is reproduced from the book by George W. Alling on *Points for Buyers and Users of Tool Steel.* From these photos and the remarks already made, the inference would be that to work a hot round bar down to a smaller section whilst it is being simultaneously revolved on its own axis must inevitably produce split centres; this, however, is not so. There

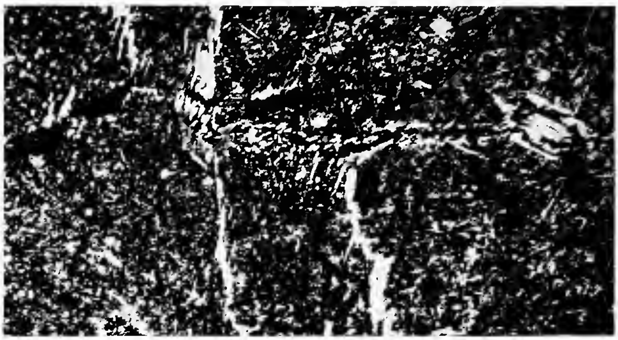


FIG. 31.—Crack following free cementite outline.

certainly is a tendency at all times for the bar to split, and it will no doubt occur if the working is sufficiently drastic and prolonged, for the simple reason that the operation produces a transverse shearing moment. Experience, however, has shown that when the operation is carried out under identical conditions some bars will split and some will not, and even one end of a bar may split in the centre and the other end remain quite sound.

After being made aware that bars behaved in the erratic manner indicated, the author used the simultaneous revolving and extending of hot bars as a means of testing the strength of the central axes of ingots, cast under different conditions. For reasons indicated in Chapter III, the central axis of an ingot is of all parts

likely to be least perfect; moreover, such imperfections do not occur uniformly along the central part of an ingot, and on that account the bars forged from any single ingot behave diversely under the specified conditions. If an ingot cast in any particular way were rolled into round bars, and these were submitted to some well-defined form of the revolving extension test, it would be found that the split centres occurred only in those bars which had formed a certain part of the ingot, and the sound bars, with equal regularity, would correspond with another part of the ingot. If ingots were cast in different ways—for example, with the narrow and wide end of taper moulds upwards—the bars made from them would behave differently; and if, finally, an ingot were "cogged" into a flat billet and, after being cut longitudinally down the centre, the halves were rolled into round bars, these would be split during the revolving-extension process only with great difficulty, if at all.

UNIFORM HEATING.

The second condition indispensable to good forging is—

(2) The steel should be heated uniformly throughout and worked under a suitable hammer.

In heating large masses of steel it is necessary to proceed slowly, as the internal stresses due to unequal cooling may be increased by a sudden application of heat beyond breaking point. So far as ordinary bar steel is concerned this danger is somewhat remote, especially if the steel has been annealed; but in handling hardened tools which have to be re-forged, incautious heating may cause them to clink in the centre. This serious flaw can be readily originated in the ordinary forged bars of high-speed steel by rapid heating even below redness, and, as is shown on p. 127, a hardened bar on being re-heated may pull itself in two under certain circumstances. It is therefore necessary to heat any hardened piece of steel very slowly, more especially such pieces as are circular in section.

If the hammer is too small for its purpose the force of the blow does not extend to the centre of the bar, and consequently the inside and outside of the heated steel are not extended at the same rate. The same thing, or

something worse, occurs in spite of a suitable hammer if the centre of the bar is colder than the outer portion. The outer portion then flows under pressure at a greater rate, and the inner portion is either broken up or becomes a core over which the softer material is stretched. The disadvantage of either alternative is so obvious that no special illustration of it is necessary.

To thicken the diameter of a bar by hammering it

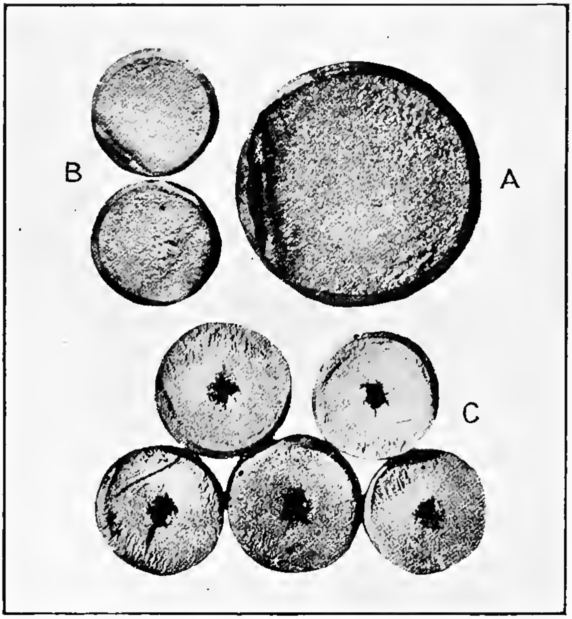


FIG. 32.—Split centres in round bars.

A represents the original bar,
B the fracture after the bar has been properly reduced in section, and
C after attempting to reduce throughout in the form of a round.

end on is wisely regarded as objectionable, though it is sometimes unavoidable. To raise pieces of steel two or three inches long, cut from bars two or three inches square, up to forging heat and flatten them under a steam hammer at one mighty blow gives an excellent idea of their comparative forging qualities, and also exhibits on a grand scale the kinds of defects which may be expected to arise when material is forged end on. Apart from

those due to imperfections in the steel itself, the greatest danger lies in the material folding on itself and forming creases which are in all respects like transverse laps. If the bar so forged is hollow—say, a rock drill on which

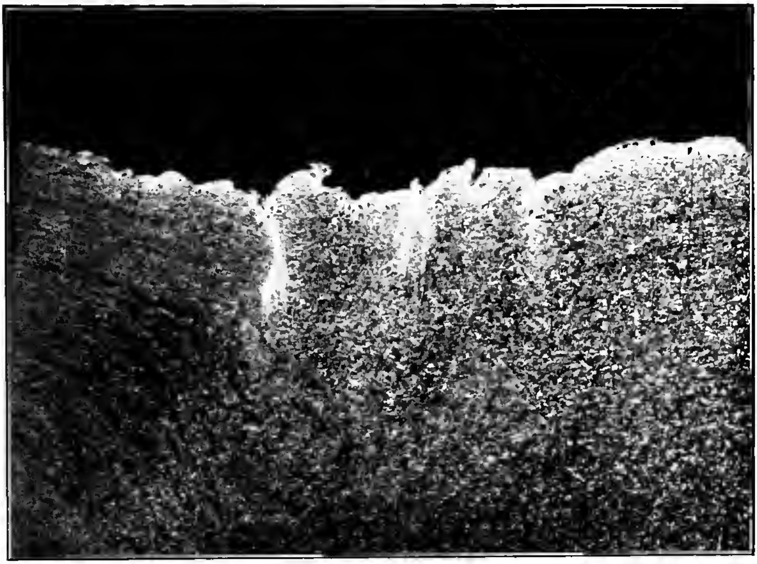


FIG. 32*a*.—Transverse laps or creases inside thickened hollow forging × 10.

a shoulder is being formed—then the creases may occur internally, and will lead to cracks through the thickened part in spite of its apparent superior strength. Creases in such a drill outlined by free ferrite are to be seen in Fig. 32*a*.

VI

ANNEALING TOOL STEEL

No object, however simple in shape, is in an ideal state after forging; and the more complicated shapes are subject to a number of ills due to irregular extension, cold working, irregular cooling, and so on. The steel may also have a coarse crystalline structure in the thicker parts owing to

Fig. 33.—Slip bands in electro-melted iron.

want of work after being exposed to a forging heat. The object of annealing is to safeguard the tools against the accumulative effect of these ills.

Machining stresses.

It is sometimes necessary to relieve machining stresses in tools which have not been heated at all, but milled or planed direct from the annealed bar. The side of a reamer, for example, which has been milled with a blunt tool is

distorted more than the remaining sides would be if cut with a sharp tool, and on hardening will warp accordingly unless previously annealed. A similar result might be expected in an object prepared in the lathe if much more material had been turned from one side of it than the other.

The appearance of distortion arising from such causes may be easily detected by means of the microscope in iron or in mild steels. In its simplest form the distor-

FIG. 34.—Distortion on roughly-machined surface × 100.

tion is visible in iron as slip-bands (Fig. 33) that appear as hatched lines extending almost to the boundary of the respective crystals in which they occur. In mild steel distortion may be recognized by the confused arrangement and outlines of the ferrite and pearlite areas, and in many cases it is possible, by sectioning the specimen in two or more ways, to determine the direction in which the distortion stresses have been applied, as in Fig. 34, which shows part of the inner surfaces of a hole bored rapidly with a twist drill.

The evils arising from distorted surfaces during subsequent operations such as hardening, or during use, when

they act as starting-points for extended cracks caused either by working stresses or corrosion, will be at once acknowledged, as it is quite obvious to any person who has thoughtfully bent a piece of metal backwards and forwards until it breaks that a distorted surface must favour the formation of cracks and fractures under any and all circumstances that are known to produce them. It is, however, useful to note, for the present purpose, that heavy cuts with high-speed steels and the general increase in rapidity of working due to the use of more powerful machines has multiplied the number of distorted surfaces regularly occurring in manufacturing operations, and has multiplied also the number of complaints to steelmakers, who are only indirectly, if at all, responsible.

SUITABLE TEMPERATURES.

Both distortion and overheating can be remedied, at least for the most part, by a simple form of heat-treatment. It is necessary only to heat the steel to a temperature which causes both ferrite and pearlite, or pearlite and cementite, to inter-diffuse, as explained on pp. 74–77, followed by cooling at a fairly uniform rate. Such temperatures are as follows, the figures being

Per cent. Carbon in Steel.	Minimum Refining Temperature.
·20	870° C.
·40	810° C.
·60	780° C.
·90	750° C.
1·10	830° C.
1·30	890° C.

minima which may be increased by 20° C. or 30° C. without any harm being done during short exposures. A long exposure is not required, and would be harmful at the higher temperatures.

The usual object of annealing in the tool room is to make the steel as soft as possible for machining purposes, although softness and satisfactory machining properties are not always synonymous terms. The two features are, however, combined in steel which, being previously hardened, has been re-heated to a tempera-

ture nearly, but not quite, reaching that at which on re-quenching it would again harden, and this condition of steel is so much to be desired that we may usefully consider it and the ease or otherwise of its attainment.

If we begin with a steel which has been hardened by water-quenching or otherwise, we know that on re-heating the same at 100°, 200°, 300°, 400° C., and so on, it becomes softer; not uniformly so with the rise in temperature, perhaps, especially as the temperature hovers about 400° C. At rather more than 500° C. a sensation of redness in the steel can be seen if the room has been darkened, and after cooling thence, whether slowly or quickly, a tool steel containing about one per cent. carbon would have a Brinell hardness number of approximately 320. After re-heating to higher temperatures the Brinell number decreases, but it is almost a matter of indifference, so far as its hardness is concerned, whether the steel is allowed to cool in the air or is quenched out in cold water. At a re-heating temperature of 700° C. we are on the verge of a sudden change, whose effect is clearly illustrated by the following table of temperatures and Brinell hardness numerals, and Fig. 35.

Re-heated to.	Cooled in air.	Quenched in water.
720° C.	187	187
725° C.	170	187
750° C.	196	555
850° C.	241	555
950° C.	269	555

These observations teach us that if it is intended to soften steel quickly by re-heating to a certain temperature, followed by cooling, say, in the air, then the nearer the maximum temperature reached approaches the temperature at which it would harden if water-quenched the softer it becomes. If, however, this temperature is overstepped the steel after cooling is harder, and in endeavouring to attain the highest degree of softness the temperature is apt to be pushed too far, and produce instead steel parts of a mixed kind, some being harder

TEMPER SOFTENING.

than the others, which is always undesirable if machining work at fixed piecework rates has to be done.

The remaining alternative is to re-heat the steel to a temperature slightly exceeding that at which it would harden if water-quenched, and to make the subsequent cooling so slow that it remains suitably soft. It is not essential to keep the steel in the furnace until it becomes quite cold; when it is no longer visibly red the cooling may be completed with doors and dampers up, or even by water-quenching.

The quicker method of softening does nothing to

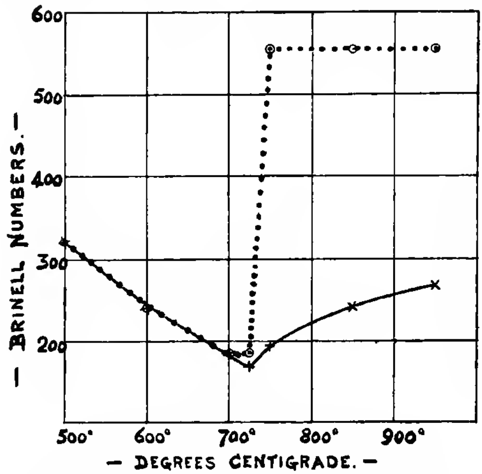


FIG. 35.—Softening of tool steel by tempering.

remedy the effects of any previous overheating, and the steel does not attain its softest possible condition. But material machines cleanly after such treatment, and it is sometimes worth while to harden it previously in order to combine the highest degree of machined finish with the mechanical properties of a hardened and tempered steel. The slower method produces softer material which cuts more easily, but less sweetly; it can also be made into a refining operation by choosing a suitable minimum re-heating temperature.

SLOW COOLING. A slower rate of cooling than is required to ensure the desired degree of softness and freedom from disagreeable stresses should be avoided. Very slow cooling from

temperatures above the critical thermal range tends to dispose the constituents of the steel in large masses, just as the slow cooling of supersaturated solutions favours the deposition of large crystals, and the net result is a deterioration of those mechanical properties of the material which may be called upon to resist either vibratory or shock stresses. This disaster occurs with surprising readiness in high carbon steels which have been cold-rolled or drawn, that portion of the carbon existing as free cementite being the first to assume the graphitic form. It is not clear why cold-working should promote this change, except we know that its tendency always is to aid materials in assuming their most stable condition. A neat illustration of this principle—it could hardly be called a law—is frequently to be seen when glass tubing is being bent or drawn out to a point over a flame; at the position where the material is not hot enough to flow the clear vitreous glass becomes opalescent and crystalline, *i. e.* passes into a more stable condition. The formation of graphite in cold-rolled high carbon steel has given a great deal of trouble to makers of safety-razor blades. A microphoto of a blade defective in this respect is shown, in the unetched condition, in Fig. 36. The graphite is seen to occupy the position formerly occupied by free cementite, and it is easy to understand the complaint that the ground edge of the blade splintered off as quickly as it could be formed. To remedy such troubles one might use steel containing no free cementite, the desired hardness being attained in other ways; or if free cementite is thought to be indispensable, then the worked sheet might be softened by tempering, or even by annealing at lower temperatures than are required to cause entire or partial diffusion of the free cementite.

Prolonged heating below the carbon change-point, *i. e.* between 680° and 720° C., should also be avoided, because it tends to form coarse laminations in the pearlite areas, particularly if the steels contain only small amounts of manganese. Laminated pearlite as seen on a polished and etched surface is very beautiful, but here as else-

where the appearance of the microsection is the only attractive feature there is about steels in which the constituents are distinctly separated and well defined. If the rate of cooling were made sufficiently slow during annealing the steel could be resolved into its constituent elements, iron and carbon (graphite), in which state its usefulness for toolmaking purposes would be extremely limited.

IRREGULAR HEATING.

A very interesting illustration of the effects of irregular heating followed by slow cooling is known to makers of

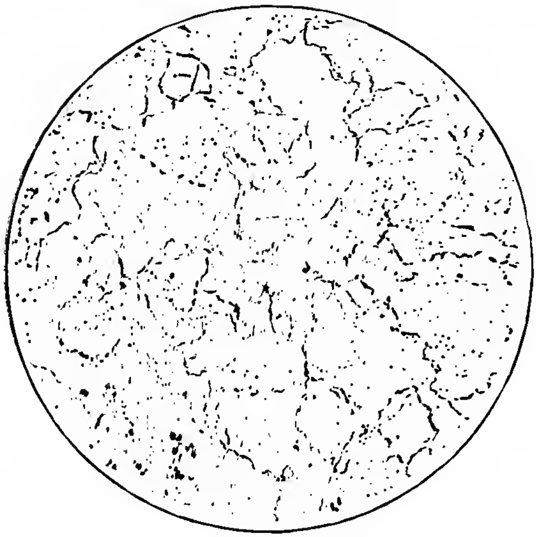


FIG. 36.—Graphite in safety-razor blade × 300.

hardened and tempered steel wire. During annealing, between drawing operations, the coils of wire are packed into pots and heated to a temperature of about 700° C. But the temperature is not always uniform, and it may happen that part of a coil will be at, say, 745° C., *i. e.* above the carbon change-point, and the remainder of the coil not hotter than, say, 730° C., *i. e.* below the carbon change-point. During the subsequent slow cooling of that part of the wire at the higher temperature the pearlite areas in it will be formed on a relatively coarse scale; the pearlite areas in the rest of the wire, which

has been heated to the lower temperature, are not appreciably disturbed. The comparative coarseness of

FIG. 37.—Wire heated to higher temperature × 300.

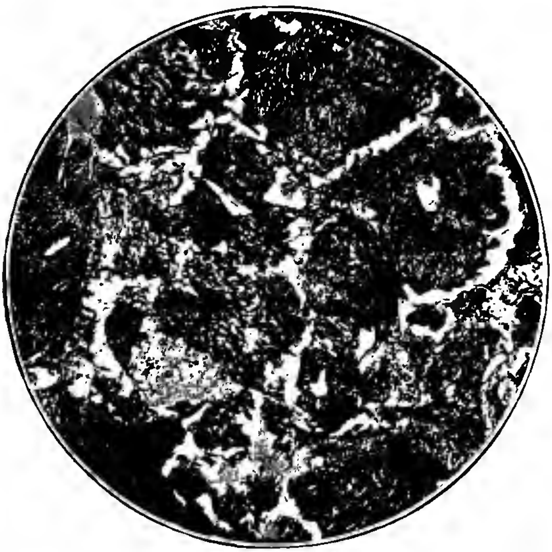


FIG. 38.—Wire heated to lower temperature × 300.

the pearlite laminations in these two parts of the wire may be illustrated by Figs. 37 and 38.

Assume now that the wire, having been re-drawn, is hardened and tempered by passing through bunsen flames, an oil tank and a hot-lead bath arranged in series. Small-gauge wire will be passed through such an arrangement at the rate of 200 feet per minute, and each part of it will traverse the heating area in about the one-hundredth part of a minute. This means that within a period of time of just over half a second the wire is brought up to red heat, and the laminæ in its pearlite areas must inter-diffuse if complete hardening in the oil bath is to take place. Obviously the time

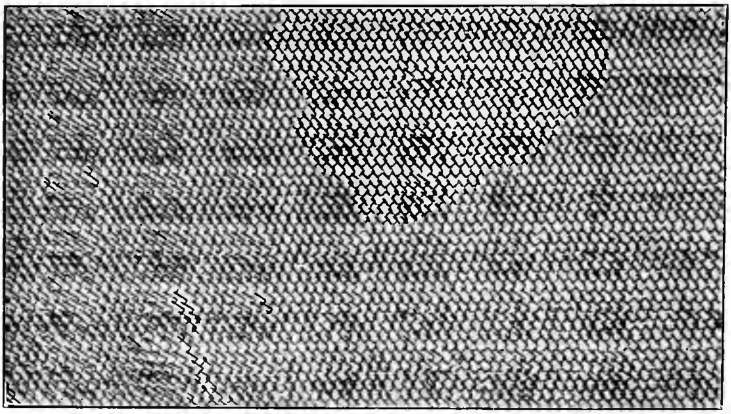


FIG. 39.—Banded appearance in defective card clothing.

required to bring about complete inter-diffusion in the pearlite will vary, depending on the coarseness of the alternate laminæ of iron and iron carbide of which the pearlite is composed, just in the same way as well-defined sugar crystals dissolve less readily than fine granular sugar.

CARDING WIRE.

In the brief space of time available the wire is hardened most completely in that part typified by Fig. 38; in that part typified by Fig. 37 the coarser pearlite has not completely inter-diffused and the wire is imperfectly hardened. If the assumed material is carding wire the softer parts of it become conspicuous in the "clothing" as faulty bands, which are repeated at regular intervals, depending exactly on the size of the coil as annealed

and the degree to which it has been subsequently drawn. Such a defective piece of card clothing is represented by Fig. 39, and as part of this waste material is used in machine shops for cleaning dirty or "pitted" files, etc., the reader may be interested in making comparative hardness tests on its darker and lighter shaded parts.

VII

PHYSICAL CHANGES IN STEEL ON HEATING AND COOLING

For a better understanding of the hardening operation, it seems desirable to interpose a chapter on the physical changes which take place when a piece of steel is heated and cooled. Before the microscope and the methods of physical chemistry were applied to the study of iron and steel and other metals, the arrangement of those parts of a text-book connecting composition and properties had necessarily many points in common with the usual arrangement of a cookery-book—and the materialized instructions were sometimes equally disastrous and inexplicable. It is now, however, possible to see resemblances between the behaviour of steel and other more manageable and simpler things which enable us to think more clearly of the varied mechanical properties which may be induced in one and the same piece of steel; and also to express ourselves, or even to some extent to offer explanations, in terms of minute structural arrangements which can be observed by means of the microscope.

STRUCTURAL CHANGES

The changes which take place on heating can be most easily followed in a piece of mild steel. Take, for example, the material whose structure in the soft state is represented by Fig. 40.

STRUCTURAL CHANGES.

If a small piece of this steel were heated to any temperature below 700° C. and quenched in the coldest water, it would not harden or in any way change its structure. If, however, it were heated to 750° C. and

quenched, it would afterwards be much harder and break rather than bend over. Let us now re-grind the quenched piece and observe, after preparing it for the microscope, that it still consists of black and white areas (Fig. 41).

If we tested one of the white areas with a centre punch we should find it almost as soft as wrought iron, but the dark areas struck in the same way would turn the point of the punch like a piece of hardened tool steel. The simplest way of illustrating this difference is to scratch

FIG. 40.—0·35 per cent. carbon steel in soft state.

the surface of the specimen with the point of the needle, and notice that whereas the white areas are deeply scored, the dark areas remain comparatively untouched.

MARTENSITE.

In comparing the structure of the steel, Fig. 40 before, and Fig. 41 after, the above treatment we observe: (1) that the dark areas after quenching occupy about the same proportion of the field as before, and (2) that the dark areas are no longer resolvable under any microscopic power available into alternating laminæ or any other arrangement of more than one substance. That is to say, the separate constituents of pearlite, however distinctly divided, as in Fig. 4, before heating,

diffuse into one homogeneous mass when a certain temperature is reached, and may be trapped by sudden quenching before they have time to return to their original form. This condition of diffused pearlite made permanent by sudden cooling is known as martensite [1] or hardenite.

If, instead of retaining our specimen at 750° C., the temperature were increased, then a gradual inter-diffusion of the ferrite and pearlite areas would take place as

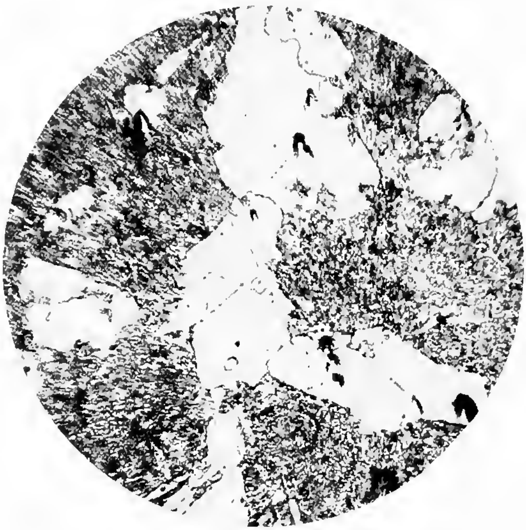


FIG. 41.—0·35 per cent. carbon steel in which pearlite areas are transformed to martensite by water-quenching after heating at 750° C. for ten minutes.

indicated by Fig. 42. And finally, at a higher temperature the diffusion would be complete, and no trace of the separate areas would be microscopically visible in the quenched specimen. In Fig. 43 the diffusion is nearly completed.

Although not perhaps strictly accurate, it may be said that in mild steel the property of being hardened is assumed in two stages.

(1) The transformation in the pearlite areas only, and

[1] After Martens, the director of the Materialprüfungsamt in Berlin, who was one of the earliest, following Sorby, to apply the microscope to the study of steel.

(2) The inter-diffusion of the transformed pearlite and the apparently unchanged ferrite areas.

HARDENING MILD STEEL.

From the above statements it may be seen that the change which permits a piece of mild steel to be hardened only in the pearlite areas takes place at a lower temperature than is necessary to effect complete inter-diffusion of these with the ferrite areas. If, however, the pearlite areas cover the entire field, as is the case when the carbon exceeds 0·9 per cent., then there is no purpose either in prolonging the time or increasing the temperature beyond the point necessary to effect the

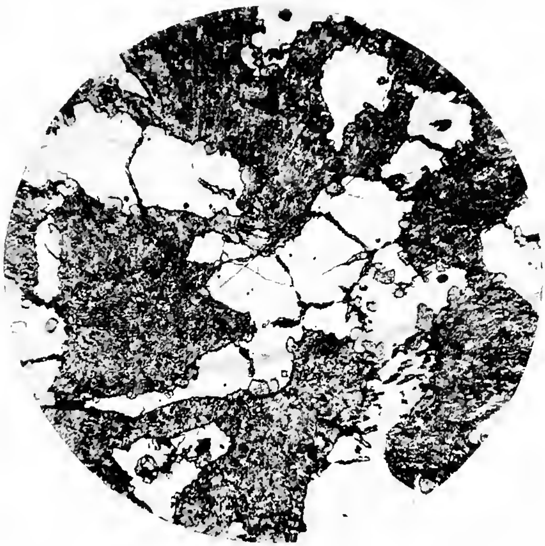


FIG. 42.—0·35 per cent. carbon steel, showing how martensite begins to diffuse.

first change. On these grounds the practice of hardening the higher carbon steels from a lower temperature is justified and explained. It is, however, quite erroneous to suppose that a piece of steel containing, say, 0·6 per cent. of carbon, could not be hardened at all at the minimum temperature required by a steel containing, say, 1·0 per cent. carbon. The same change would take place in both steels at approximately the same temperature, the only difference being that in the former a higher temperature would be necessary to obliterate the ferrite

visible in Fig. 5, for example, whereas in the latter case this consideration does not arise because no free ferrite, either as cell walls or otherwise, exists in the steel.

SLOW COOLING.

The quenching of a piece of mild steel from a temperature well above the minimum at which it will harden, preserves the material in a state differing entirely, in a structural sense, from the normal or forged state, and probably also from the actual structure of the red-hot steel. But on allowing the specimen to cool slowly, we

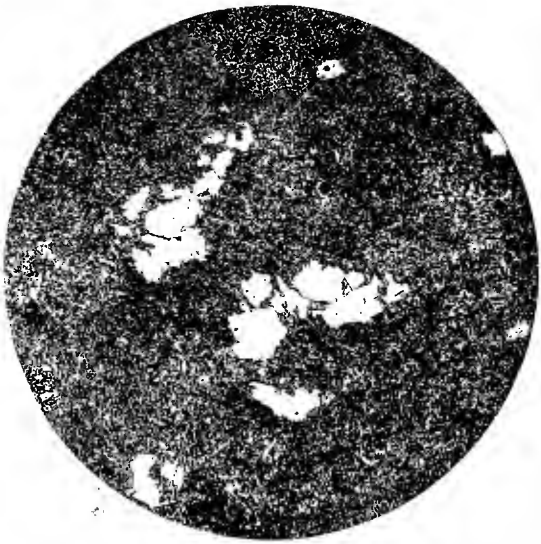


FIG. 43.—0·35 per cent. carbon steel in which the diffusion is nearly finished.

get back ultimately to the original starting-point through a series of changes something like the reverse of those which took place on heating. That is to say, the ferrite areas which were the last traces of the original pattern to disappear on heating, are the first to reappear on cooling. Very gradually increasing in size, they finally occupy the same relative amount of space as before; then the black areas break up again into intimately associated plates or particles which form pearlite, and no quenching, however vigorous, once this point is passed, can cause the steel to harden appreciably. The changes

may be represented broadly, though not entirely, by Figs. 40 to 43 taken in the reverse order.

It is not necessary to bestow more than a passing glance on the thermal behaviour of very high carbon steels containing cementite. This constituent remains in well-hardened industrial tools pretty much as it existed in forged materials from which they were made. It does not change its location or assume any very definite part in the physical changes which take place, unless the tool happens to be heated much above its minimum hardening temperature. It then diffuses into the surrounding material, and oftener than not the tool cracks on hardening. Such cracks have a great tendency to extend along the junction lines between the grains. CEMENTITE.

The use of steels containing free cementite is, as we have seen on p. 8, only permissible for tools which can be operated without shock. Its use, however, is highly advantageous under these restricted circumstances, because cementite is harder than any other constituent either natural or induced, and therefore serves a useful purpose where actual mechanical wear, as at the point of a turning tool or the hole of a draw-plate, has to be avoided.

THERMAL CHANGES

That snow or ice becomes liquid if salt is thrown on it is a fact known to everybody. If, however, a mixture of snow and salt containing 23·5 per cent. of the latter were prepared at a temperature $-30°$ C., it would remain as dry and solid as a similar mixture of sand and sugar. But if the temperature rose only slightly above $-22°$ C., the salt and snow would begin to interpenetrate and become first moist and then quite liquid. Above $-22°$ C. the mixture would remain liquid; below $-22°$ C. it would again become quite solid and consist of separate particles of ice and salt existing side by side; at $-22°$ C. it could be either liquid or solid, but to convert it from one state to the other it would be necessary to add or subtract heat. SNOW AND SALT.

LEAD AND ANTIMONY.

Consider also the similar behaviour of a mixture of lead and antimony. In the pure state lead melts at 327° C., and antimony at 632° C. If we prepare a mixture of very fine filings containing 13 parts of antimony and 87 parts of lead, and press these together into a compact piece and again reduce it to fine filings, we shall obtain an intimate mixture of lead and antimony particles. If these be again pressed together and heated, we shall find that they melt into a perfectly homogeneous liquid at 250° C., which is considerably below the melting-point of either lead or antimony. In the liquid state neither of the metals would be separately distinguishable; but in the solid state the mass will consist, however often it may have been melted, of particles or plates of lead alternating with particles or plates of antimony. The temperature of 247° C., at which the mixture begins to solidify on cooling, remains unchanged until the mass is quite solid; the temperature cannot sink before this state is reached, no matter how cold the surrounding atmosphere may be, and conversely on heating. This means that if a thermometer were placed at, say, 300° C. in the lead-antimony mixture which was being allowed to cool, we should observe a gradual and continuous fall in temperature until 247° C. was reached. Then the cooling operation would be arrested, and the thermometer kept stationary by the heat liberated during the change from the liquid to the solid state, whence it would again fall gradually to normal temperatures. This entire cooling process might be graphically represented by Fig. 44.

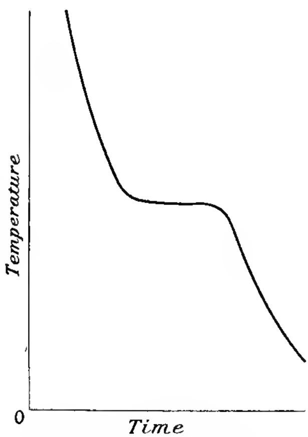


FIG. 44.—Cooling curve of eutectic mixture.

The thermal behaviour of a piece of tool steel, and many other metallic alloys, is precisely similar to the salt-snow and antimony-lead systems, which are intro-

duced here only because any reader sufficiently interested to make personal observations will find them much easier to handle than molten and solid steel. The structural arrangement is very similar (compare Figs. 45 and 46), and the variations when a certain temperature, characteristic of each case is reached, is between alternating plates of two constituents on the one hand, and solid (diffusions) or liquid solutions on the other, heat being liberated or absorbed according to the direction of the change.

FIG. 45.—Lead-antimony eutectic.

TOOL STEEL.

Owing to the liberation or absorption of heat which accompanies the change of iron carbide from one state to the other, we are able, by means of an arrangement for accurately measuring temperatures, to conduct a sort of thermal analysis. So far as tool steel is concerned, we need study only one typical example, *i.e.* a 0·9 per cent. carbon steel. On heating such a steel, say at the rate of one degree per second, we may represent the rise in temperature by a straight line sloping upwards. Up to a certain point the straight line

correctly represents the rise in temperature, both of the steel and the furnace containing it. But at about 740° C. there occurs a period of many seconds during which, although the furnace is getting hotter, the temperature of the piece of steel itself does not rise at all. During this period, the adjacent constituents of the pearlite are diffusing into each other, *i. e.* dissolving each other, and absorbing a certain amount of heat in the process, just as salt causes an absorption of heat

FIG. 46.—Iron-ironcarbide eutectoid.

and makes a freezing mixture when it dissolves in snow. As soon as this absorption of heat can no longer counterbalance the heating effect of the furnace, the temperature of the steel rises again. The entire procedure may be represented by a line, ACM, with a kink at C (see Fig. 47).

It is an easy matter, by means of a delicate pyrometer suitably arranged, to follow the heating of a piece of steel in the above manner and fix the actual temperature at which the point or period C occurs. Its occurrence coincides, of course, with the structural changes which we connected in the last section with the property of

hardening, *i.e.* only when a piece of steel has been heated beyond the temperature C can it be hardened by quenching.

But the existence of the critical point C and the actual absorption of heat accompanying it can be easily demonstrated in the following manner. In a smith's fire which has burned hollow, or any other uniform source of heat, place a wedge-shaped piece of steel—a chisel, for example—and notice that after becoming red-hot the extreme edge suddenly becomes colder or darker. This darker band gradually travels from the point up the thicker part of the wedge and indicates the position on the chisel in which the critical thermal change is taking place. The temperature is actually less on the darkened band than it is either above or below it, and yet if the chisel be quenched it will be hardened only up to the dark band, and not beyond it. This observation can be applied to the hardening of chisels, sates, mill-picks, axes, and numerous other tools utilized by the smith, the bridge-builder, the miller or the wood-cutter, in regions where most forms of pyrometers would be useless, although a good tool is none the less desirable. Workmen who have not the remotest idea what it means have used this phenomenon as a "tell-tale," or indicator, to show when a desired state or degree of temperature has been attained.

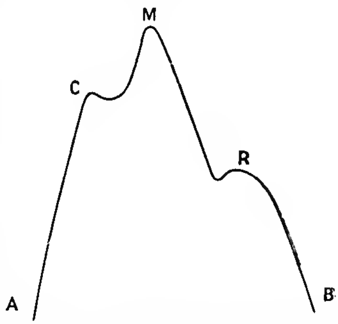


FIG. 47.—Thermal curve of 0·9 per cent. carbon steel.

To return to Fig. 47. If instead of quenching the piece of steel we allow it to cool, also at the rate of one degree per second, we observe at a temperature of 690° C., or thereabouts, a period of many seconds during which the steel does not cool at all. It may, indeed, get hotter, although all the time the furnace is cooling down. The cooling process reverses the changes which take place on heating, and may be represented by the

line MRB. Both the break at R and at C are of great importance to the steel hardener, and their meaning is simply this—

> From any temperature above C a piece of steel will harden if quenched, but at no lower temperature. If, however, the steel has already been heated beyond C, it can be hardened by quenching from any temperature not below R.

The points C (calescence) and R (recalescence) are known as critical temperatures or change points. Their positions do not alter much in ordinary kinds of tool steel, although the carbon may vary between 0·7 and 1·5 per cent., but they are greatly affected by adding tungsten, chromium, or nickel to the steel.

As means for making thermal curves and observing the influence exerted on the position of the critical points by variations in composition, rate of heating and cooling, initial cooling temperature, and so on, is a desirable addition to the equipment of every first-rate hardening plant, the author has ventured to illustrate and describe on p. 212 an arrangement suitable for works purposes.

CRITICAL DENSITY CHANGES

The variable expansion on hardening of different sizes and shapes is an endless source of trouble to the maker of gauges and fine tools. How delighted he would be with a steel which on hardening neither expanded nor contracted, or even with a steel whose changed dimensions could be calculated beforehand. Such an ideal steel, however, has not yet been produced, for the simple reason that it is scarcely compatible with the nature of the hardening property of steel. Some steels, of course, come nearer the ideal than others.

VOLUME CHANGES. The volume of a piece of steel always increases on hardening, although in the case of a bar its length may shorten, and in a sheet both length and breadth generally decrease. It may, indeed, as a rule, be assumed that the main increase in size of a piece of quenched steel lies at right angles to the plane of the cooling surfaces,

in other directions it often decreases. The reason for the net increase in size is that the new constituent formed above the calescence point, as made permanent by sudden cooling, has a lower specific gravity than the constituents out of which it was formed. On this account the quicker the cooling, or the higher the quenching temperature (within reasonable limits), the greater is the increase in volume, though this statement is possibly not without exception.

A series of steel rods of varying thickness were hardened under the same conditions, and subsequently tempered by Fromme. He then determined their relative volumes, taking the volume of the unhardened steel as unity, with the following results—

Condition of rod.	Vol. of rod, 7 mm. rd.	Vol. of rod, 4·2 mm. rd.	Vol. of rod, 2·65 mm. rd.	Vol. of rod, 2·55 mm. rd.
Unhardened . . .	1·00000	1·00000	1·00000	1·00000
Dead hard . . .	1·00772	1·01000	1·01285	1·01210
Tempered, yellow .	1·00347	1·00495	1·00660	1·00620
,, blue . .	1·00217	1·00425	1·00370	1·00205
,, grey . .	0·99957	1·00060	1·00055	0·99930

These results show not only that the thinner sections increase more in volume, but also that tempering reverses this change. The variation in specific gravity due to tempering has been more recently investigated by Maurer, whose results are expressed diagrammatically in Fig. 48.

In addition to these variations in density, of which steel-hardeners are perfectly well aware, there is another critical change that takes place on cooling (and in the reverse order on heating) of which less notice has been taken, though its effects are often very serious. These changes may be explained by the aid of Fig. 49, which represents the thermal curve and also the expansion and contraction curve of a steel containing ·70 per cent. carbon and 2·50 per cent. silicon. CRITICAL EXPANSION.

Starting at the bottom left-hand corner, the curves show a gradual rise in temperature of the material,

accompanied by an expansion of the test bar (the bar was 100 mm. long), until a temperature of about 820° C. is reached. The marked thermal behaviour of the bar at that temperature is accompanied by a halt in the rate of expansion, followed by an actual contraction; and before the normal rate of expansion is again attained the temperature has risen over a considerable range.

On cooling, the temperature falls uniformly until at

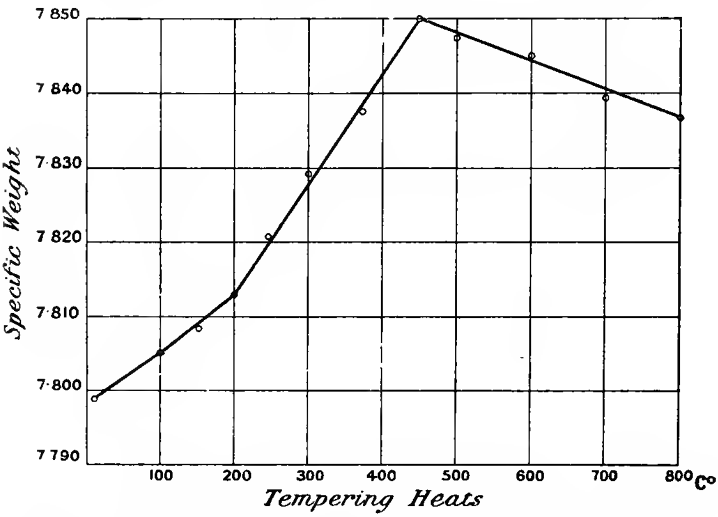


Fig. 48.—Variation in specific gravity due to tempering water-hardened tool steel.

730° C. an evolution of heat is actually registered, and this is accompanied by a corresponding expansion in the length of the bar. The indication of surfusion in the dotted thermal curve and the associated closed loops in the full line expansion and contraction curves is of interest, but not material to our present purpose.

Consider now the influence which these critical volume changes may exert during the heating of delicate tools. In whatever kind of furnace they may be heated there is no possibility of the change taking place in every part at exactly the same moment; and if the thinner parts of an object are contracting at the same time as

the thicker parts are expanding, then harmful stress or even distortion must arise. With the intention of avoiding such defects certain kinds of small tools are heated with extreme slowness, say during six hours instead of in half an hour, and though the improved results are ample remuneration for the trouble involved they are at best imperfect.

The substance of the last few paragraphs points clearly to the advantages of preheating, and indicates with

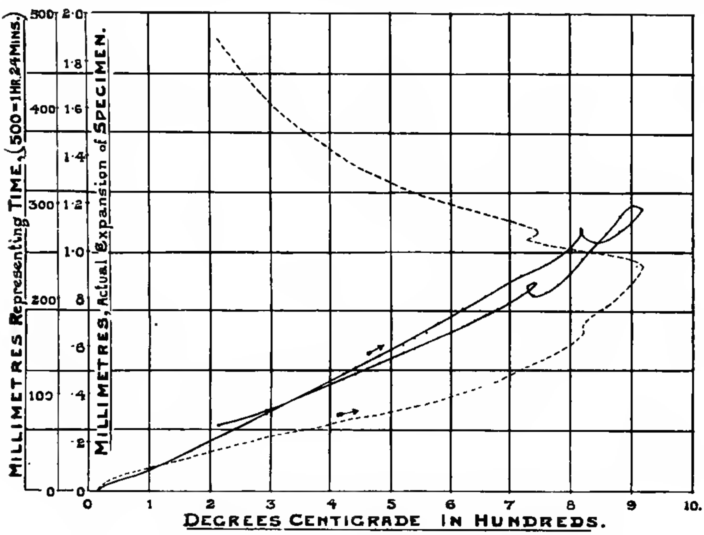


FIG. 49.—Thermal and expansion-contraction curves.

equal clearness that the temperature of the preheating furnace should be as near the critical temperature of the steel being handled as possible, and certainly not up to it. With this precaution the rate of heating in the first furnace is of less importance, but the slower the rate of heating in the second (hardening) furnace the better.

The special importance of the critical expansion during the cooling of steel comes out in a very disagreeable manner on quenching large objects of circular section. Generally speaking, the risk of hardening a piece of round steel which requires to be glass-hard on the surface increases with its diameter. Small steel rolls, large

taps, broaches and reamers will readily split along their entire length, unless carefully handled. It is frequently assumed that such tools split because "the outer parts shrink on the inner in the cooling; this evokes a reaction pressure of the inside on the outside which is greater in proportion as the temperature is greater on the outside as compared with the inside, *i. e.* the thicker the steel is.[1]

The above explanation is very difficult to follow, and may preferably be replaced by the more obvious suggestion contained in Fig. 49, viz. if the outside of a round steel object becomes quite hard before the inner portion has been cooled below the temperature at which the critical expansion takes place, then, when it does take place, the hardened exterior, if it cannot yield, must break.[2] The breaking of a hardened steel ring by expansive forces from within (by a drift) takes place readily. The special danger of round bars is discussed on p. 126, and the proper handling of large-toothed cylindrical tools on p. 107. The practice of boring out the centre of steel rolls before hardening in order to prevent cracks facilitates the cooling of the inner portions below the critical temperature before the outer surfaces become quite cold and hard.

[1] Reiser, *The Hardening and Tempering of Steel*, p. 23.

[2] On p. 9 of his highly commendable book, edition dated 1863, Ede states that the "expansion of the middle is more than the outside can bear, and thus articles crack," but he was not able at that time to explain why the middle portions expanded.

VIII

THE HARDENING OF STEEL

THE hardening operation in toolmaking is of the greatest importance. It shows up defects in material which were not before noticeable, and it exaggerates the faults of every previous operation. The science of it can be expressed in a few short paragraphs; the art may well become the study of a lifetime.

COMMON-PLACE REMARKS.

A piece of steel is in the best condition for hardening after it has been properly annealed. The heating of large pieces and complicated shapes should be gradual, and care taken that corners, cutting edges, and other thin parts are neither overheated nor decarburized. These statements are very commonplace, but do not unfortunately describe the common practice. The best kind of furnace is one in which a large-enough area of it can be maintained at any desired uniform temperature. Whether this be a reverbatory hearth, or a bath of molten lead or salts, or a muffle furnace must depend on local circumstances. We have already seen that a piece of steel quenched from above the hardening temperature remains permanently expanded. But as the hardness and consequent permanent expansion on the surface and in the interior are not equal, so each piece of hardened steel of a considerable size is in the act of being pulled apart and may resist that tendency very easily or otherwise. If, however, to the unavoidable tension there is added—due to overheating—a coarse structure, which is physically weak, we have the most favourable opportunity for cracking or breaking either during or shortly after quenching. It is evident, then, that all tools should be hardened at the lowest possible temperature consistent with the desired properties, and the whole

science and art of hardening resolves itself into attaining this temperature in a regular and uniform manner, and in quenching the heated tool with due regard to its size, shape, etc., and the work it is required to do.

UNIFORM HEATING.

Uniform heating is much more important than a variation of a few degrees in the actual temperature, and can only be attained in a suitable furnace. The salt bath most nearly approaches the ideal kind of furnace, and is to be recommended for expensive tools wherever possible. The lead pot is also excellent; it heats objects more quickly than a salt bath, and for some purposes is to be preferred. A flat hearth gas-fired furnace is less reliable than either of the above, though it may sometimes be more convenient. If closed muffle furnaces are used, the temperature is more uniform with cast-iron or steel muffles than with fireclay ones. The worst form of furnace is the ordinary smith's hearth, though an experienced man will get quite good work out of it when nothing better is available.

It is impossible in any known form of furnace to heat up articles of varying cross-section at the same rate throughout their mass. When this limitation is considered in conjunction with the critical contraction changes described on p. 84, it will be seen that permanent distortions of considerable magnitude are unavoidable, quite apart from any question of sagging due to the weight of the object or its position in the furnace. In these days when cutters and noiseless gears have been made almost mathematically exact, no possible source of error can be overlooked. A distortion which is very obvious after quenching or even a crack may be due originally to the effects of critical contraction during heating.

HARDENING TEMPERATURES.

The minimum temperature at which hardness can be conferred on a piece of steel by sudden cooling may be sharply determined by means of the apparatus described on p. 212, in the form of a curve like Fig. 47. Useful as this information is, it must not be assumed that the best results will necessarily be attained by quenching out after heating the tool to a temperature not more than a

few degrees beyond the minimum. Both the degree of hardness and the depth to which it penetrates might vary considerably in two tools, one of which was quenched from the theoretical minimum indicated by the curve, and the other from a temperature, say, 30° C. higher. For several reasons the information afforded by the thermal curve should not be followed blindly.

(1) The temperature at which the critical change occurs varies slightly with the rate of heating, and consequently with the size of the object heated.

(2) The critical change, though no longer appreciable to our apparatus, is probably not quite completed as soon as the heating curve assumes its former course.

(3) The rate of cooling at the beginning of the quenching operation is not so rapid as it subsequently becomes (see Fig. 52), and therefore, in order that the maximum rate may be attained by the time the critical range is reached, the cooling should be started somewhat above it.

In order to avoid any uncertainty in these respects the steel should be heated some twenty to forty degrees higher than appears theoretically necessary. At this temperature the structural transformations take place quickly and completely.

FALLING HEATS.

The usual works practice is to quench out the steel from the highest heat attained; but there need be no hurry about it, as the temperature has still a long way to fall before it passes the lowest point at which the steel will harden (R in Fig. 47). Many operators hold the steel in the air for a few seconds before quenching; this is the meaning of the expression "hardening on a falling heat." There is no harm done by this delay so long as inequalities in temperature in different parts of the tool do not arise, as they certainly would if the range of temperatures through which the tool was so cooled were extended. On the other hand, there is a decided advantage in permitting the temperature of the steel to fall as low as practicable, and contract in doing so before quenching. From these considerations has arisen in recent years a practice which minimizes the risk of breakage with complicated tools, and generally decreases

the brittleness of a tool without, at the same time, decreasing its hardness. This consists in taking the tool already heated in one furnace to the required maximum temperature—say, 780° C.—and placing it into a second furnace in which it is maintained at a temperature some 10° to 20° C. above the minimum cooling change point, say, 710° to 720° C. As a second furnace the most convenient form is a salt bath, whose temperature can be easily maintained at a quite negligible cost by the heat of the objects constantly being added at a higher temperature than that at which they are withdrawn. Other features of the salt bath furnace, relative to the above purpose, are discussed on p. 147.

METCALF'S TEST.

The following means of determining in an ordinary smith's hearth the degree of redness, at which the finest-looking fracture is induced in steel by quenching, is generally attributed to Metcalf. A bar of the steel being used of about one-half inch diameter is notched for a length of three or four inches, each eight or ten millimetres from one end. The notched portion is then heated in the smith's fire until the extreme end is white-hot, and in such a manner that the heat tapers gradually backwards. After quenching, the bar is dried and broken at each successive notch. The first piece or two will break off very easily—if they do not break in quenching—and exhibit a coarse, staring white fracture. Subsequent pieces will break off less readily, and become gradually finer in fracture until the smooth amorphous appearance of well-hardened steel with a faint, bluish-grey tinge is reached. After that the fracture gets coarser down to the unhardened part.

The point about this test, which is usually emphasized, is to observe and keep in mind the precise kind of red colour which existed in the hot bar just at the spot where the best fracture was later discovered. This takes some doing. Moreover, as the precise kind of cherry-red colour, even if it had been observed, would be a reliable guide for future use only under exactly the same conditions of lighting, etc., the value of the test is obviously more apparent than real. The test is, however, of great

use in that it provides with little trouble a series of fractures representing the effect of overheating. These may be preserved in a small glass-topped box, such as is used by entomologists, and serve a very useful purpose as standards for comparison with the fracture of defective tools. In this way the hardener may convince himself of many unsuspected cases of overheating, although it should at the same time be remembered that the degree of granulation in a fracture depends not alone on the temperature, but also on the length of time during which the steel was exposed to it.

ALLING'S TEST.

A modification of the Metcalf test has been described by George W. Alling. It is not as easily carried out as the Metcalf test, but it is in some ways more instructive. Place the steel (a piece about 4″ × 1¼″ square is a convenient size) in the jaws of a milling machine, in such a position that the saw of the machine will cut nearly quarter through at one end, and about three-quarters through at the other. Then round the corners of the groove, and cut out the bottom to a "V" shape. Now submit the piece to a tapering heat, as in the Metcalf test, taking care that the overheating is done on the end least penetrated by the saw, and, after quenching, wipe perfectly dry. If a wedge is now placed in the groove, and bears on its edge the whole of its length, the two halves can be forced apart by a few smart blows, exposing a fracture, showing the effect of the varying temperatures to which the steel has been heated. A photo of pieces of steel prepared and fractured in this way is reproduced in Fig. 50.

JUDGING TEMPERATURES.

In the absence of any special means of determining and controlling the correct hardening heat, the most uniformly reliable practice is to keep handy a few half-inch bars of the steel being used, and by trial with these to fix afresh in the mind the required shade of redness as often as the conditions affecting colour may change. After quenching the bars are tested with a file and fractured with a hand hammer on the anvil. The method at best is only a makeshift, but if the man using it possesses patience and the faculty of observation, together with a

fair share of gumption, he need make no howling mistakes as far as temperatures are concerned at any rate.

The minimum temperature at which a piece of ordinary, say, one per cent. carbon steel can be hardened is about 740° C. If the steel contains 2 or 3 per cent. chromium, or 3 or 4 per cent. tungsten (magnet steel), the minimum hardening temperature will be

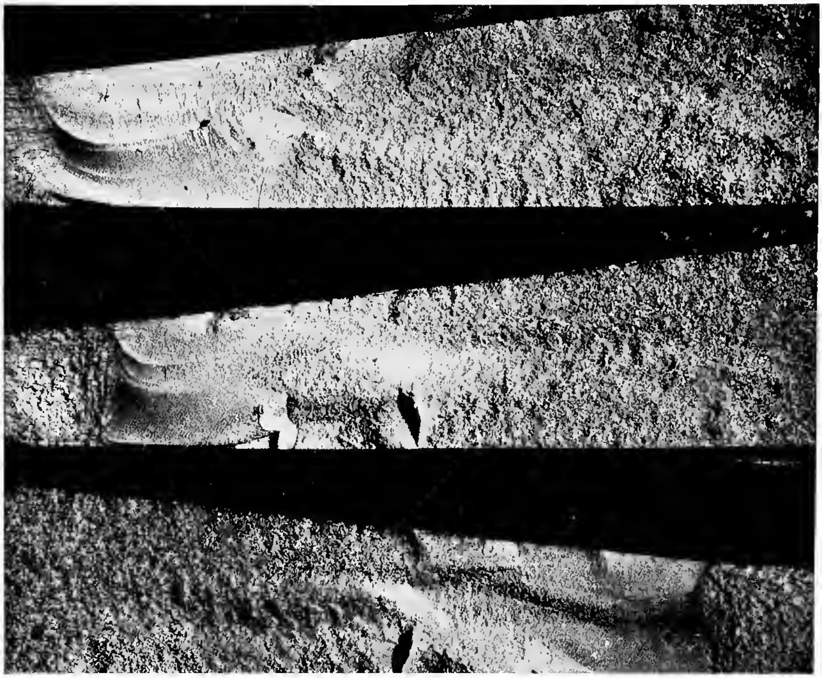


FIG. 50.—Fractured bars prepared by Alling's method.

790°–800° C. If heated beyond these temperatures the steel can be cooled to 700°–710° C., and will still harden on quenching (see Fig. 47). We may thus utilize two pieces of steel to fix three points, 700°, 750°, and 800° C. in the temperature range, which is the most suitable for the hardening of ordinary tool steel. The small strips used for cutlery purposes or small files are a handy form in which to use the steel. Cut off pieces two or three inches long, lay them in the hardening furnace, and when

they have attained the heat of the furnace quench them out. If the chromium steel hardens, the temperature is 800° C. or over; if the carbon steel hardens and the chromium steel does not, the temperature is not 800° C., but is at least 740° C. If the carbon steel is purposely made much hotter, and allowed to cool to the temperature of the hardening furnace, and on quenching it is found to harden, whereas a piece heated only to the temperature of the furnace does not harden on quenching, then the temperature is 700° C. or over, but not 750° C. These observations are merely intended to suggest that means of controlling temperatures do not necessarily involve any special outfit.

Uniformity in the rate of cooling is quite as important as uniformity in the rate of heating of the different parts. But it is very much more difficult to attain, and often impossible on account of the rapid rate at which cooling must take place in order to harden steel at all. There is endless scope for resourcefulness and ingenuity in the quenching operation, and it is unlikely that men who are not disposed to frequent experiment will ever be able to harden successfully very varied and delicate tools. QUENCHING.

Almost any desired result can be obtained by quenching in water. It may be quite cold when the tool is simple in shape and required to be glass hard, but for a less intense effect or more intricate tools it may be heated to 30° or even 40° C. If, however, the water be previously saturated with calcium chloride, which raises the boiling-point very considerably, the bath may, if required, be heated to 70° or 80° C. In this way every advantage of oil-hardening may be obtained, and others which are not obtainable with oil, although for the sake of convenience oil is generally preferred. The physical properties of solutions of calcium chloride of importance in this connection are contained in Fig. 51.

The properties of liquids which appear to have an influence on their use as quenching media are: *conductivity*, which effects a more or less rapid change of heat between different parts of the bath; *volatility*, which determines the rate of formation of vapour about the QUENCHING LIQUIDS.

steel; *viscosity*, which controls motion amongst different parts of the liquid, and has a good deal to do with uniform cooling; *specific heat*, which is a measure of the amount of heat that can be absorbed by any volume of fluid in raising its temperature through a given number of degrees; and in oils, the readiness with which a coating of charred oil is formed about large objects which do not cool very rapidly. According to Carl Benedicks,[1] the cooling property of a liquid is chiefly dependent on a high latent heat of vaporization; the specific heat, con-

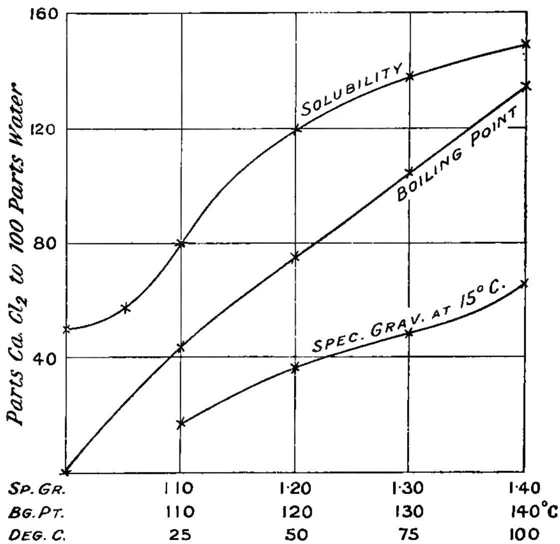


FIG. 51.—Physical properties of solutions of calcium chloride.

ductivity, and viscosity being of secondary importance. These views, however, at present appear to rest entirely on laboratory experiments, and as they do not entirely fit in with the notions of practical workmen, it seems desirable that they should be confirmed by various forms of mechanical tests made on specimens of various dimensions prepared under practical working conditions.

SUPERSTITIONS. It is not intended in the last sentence to convey the idea that any statement at variance with the views of the hardening shop is probably wrong. Although by

[1] Carnegie Researches, 1908. *J. I. & S. I.*

dint of careful observation and experiment, the hardener's handicraft was well developed before any scientific explanations of it or aids to it were available, it must be said that it has to its account a number of almost incredible notions, which to some extent are still adhered to. A certain amount of superstition may of course always be expected to gather around processes which are secretly operated. Amongst what we may call the ancient literature of this subject, we find, for example, that the urine of a red-haired boy was considered an essential constituent of a first-rate hardening fluid (see note, p. 218). As ridiculous as this may appear, it is but an illustration of the belief, not entirely abandoned, that some virtue from the fluid in which it is quenched passes into the hardened steel. How many tubs of precious (?) fluid have passed from father to son on this account? It is said that some barrels of Sheffield water were at one time shipped to America for steel-hardening purposes. The report may be unfounded, but a belief has existed amongst Sheffield cutlers for ages long that the water they use is superior to any other for hardening. Precisely the same view is taken by the cutlers of Solingen of the water used for hardening their blades.

MEASURING RATE OF COOLING.

These and similar vain beliefs in specific fluids were considerably disturbed by Le Chatelier.[1] He heated small cylinders of iron into which a thermo-couple was placed and plugged about with clay. On quenching these in various fluids he observed the relative times required to cool from 700° to 100° C. The results as plotted in curves by Haedicke [2] are reproduced in Fig. 52.

The most unexpected result was given by quicksilver (curve B). Its high conductivity, which causes the sensation of cold when touched by the finger, is responsible for the notion that it must therefore cool heated steels very quickly, and confer on them a special degree of hardness. It appears, however, to be distinctly inferior in this respect to cold water, the reason being that the specific heat of quicksilver is about thirty times

[1] *Revue de Métallurgie*, September 1904.
[2] Haedicke, *Stahl und Eisen*, 1904, p. 1239.

less than that of water. The cooling effects of brine and dilute sulphuric acid were found to be not appreciably different from ordinary water, and do not bear out the popular notion of their value as cooling agents. The effect of heating the water up to 50° C. is also not very striking, but it must be remembered that these

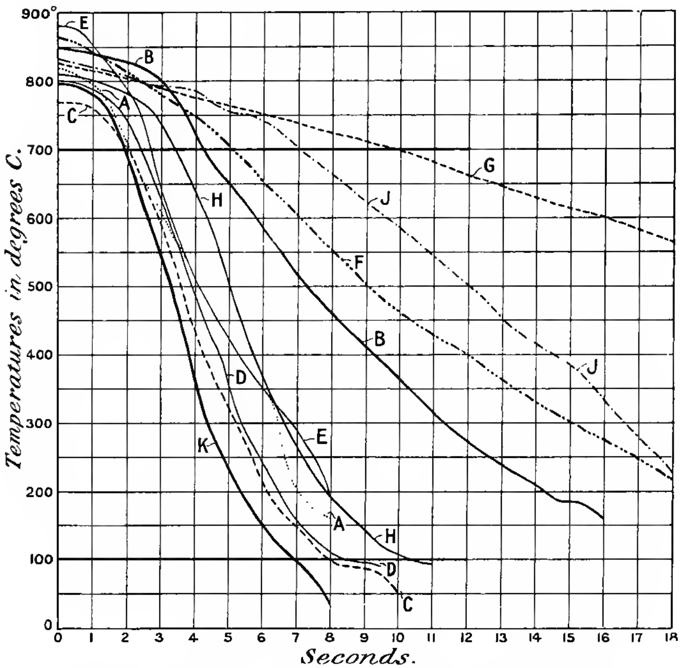


FIG. 52.—Relative rate of cooling in various liquids.

B, Quicksilver. C, Water at 20° C.
D, Salt water. E, 10 per cent. sulphuric acid.
F, Linseed oil. G, Lead.
H, Water at 50° C. J, Water at 100° C.
K, Water spray.

trials were all made on small pieces of metal weighing barely one and a half ounces.

OIL HARDENING.

From a former survey of the physical changes to which the phenomenon of hardening is due, we know that the rate of cooling fixes the degree of hardness attainable, and with the degree of hardness the change of volume and the consequent strain also varies. We know also from a consideration of thermal curves that

the hardening effect conferred by quenching is confined to a somewhat narrow range of temperature, usually between 720° and 680° C. Subsequent cooling below 680° C., however rapidly performed, does not harden the steel, but it prevents the tempering reaction which, if it were not suppressed, would make the steel quite soft again. In using oils and similar fluids as quenching media, both the cooling down to 680° C. and the cooling below that temperature take place at a slower rate than if water were used, with advantage or disadvantage according to circumstances. It is obvious that a certain minimum rate of cooling between 720° and 680° C. is necessary in order to harden any particular piece of steel to a required degree. This rate, however, varies with the composition of the steel, and nearly all high-class crucible steel which has not been especially made for oil-hardening does not harden very well in oil. To use a harder steel on this account for the same purpose does not help very much, as it does not cool more quickly, and the change in the state of the carbon proceeds at about the same rate. If, however, the amount of manganese (0·15 to 0·25 per cent.) usually present in high-quality tool steel is raised to 0·40 per cent. or over, the rate at which the critical thermal change takes place is decreased, and a tool otherwise too soft will oil-harden satisfactorily.[1]

HARDENING OIL.

There is no special virtue in whale oil or rape oil or in any other kind of oil apart from incidental physical properties such as flash-point, tendency to thicken, etc., and the rate at which it will quench heated steel. It is feasible, therefore, to fill the hardening tanks with oil which is bought for the actual service it can render, and not on account of a label or a source of origin which adds considerably to its price. The comparative value of oil for hardening purposes can be determined by observing or recording pyrometrically the rate at which

[1] The question of composition in relation to the hardening properties of tools opens up an extensive inquiry quite beyond the scope of our object, and is more the business of the steel-works than the tool-room. Very little consideration is needed, however, to show that in this respect the co-operation of the user, however familiar he may be with "tempers," and the maker of the steel is highly desirable.

a large block of steel can be cooled by immersing it in a given volume of the respective hardening fluids. For this purpose the author uses a round bar of steel, four inches in diameter, on to which a long neck has been forged or turned. A hole is drilled longitudinally to the centre just large enough to admit the fireclay insulating tubes of a thermo-couple, and the neck is extended into a handle by screwing on to it a length of wrought-iron tubing. The block of steel is heated in a small furnace, through the door of which the tube projects, to a temperature of 850° C., which is registered by the furnace couple, and also by the naked (but insulated) couple that has been passed down the tube to the bottom of the hole in the steel block.

On removing from the furnace the heated block is immersed in a circular tank containing four gallons of the hardening fluid. The block should rest undisturbed on a grid two or three inches from the bottom of the tank, and the length of the tank should permit the oil to cover the thick part of the immersed block by a depth of three or four inches. The tank should also stand in a wooden box and be packed all round and underneath with dry sand, infusorial earth, slag wool or some other non-conducting and incombustible material.

From the moment of immersion onwards the operator watches the temperature indicator and takes such observations as will enable a time-temperature quenching curve to be plotted; or, more instructively, arranges for the cooling curve to be traced out by an automatic temperature recorder.

From the observed temperature of the oil before and after the heated block has been cooled in it, and from the known weight of the block and the oil, the approximate specific heat of the oil can be calculated. But its effectiveness as a quenching medium is determined from the steepness of the quenching curve, and may be confirmed by sawing through the block just below the end of the central hole and making a series of Brinnell hardness tests across the sawn face. The results obtained are comparative only, but so also is the question to be

answered, viz. whether the new or cheaper oil is a reliable substitute for the oil previously used.

This simple form of test can be used as described only for observing the comparative quenching values of material of the same class. If it were used, for example, to compare the quenching value of water and oil the results would indicate that they were about equally effective, the reason for this obvious misrepresentation being that the water boils at a much lower temperature than the oil and the block becomes insulated by a layer of steam. If instead of allowing the block to rest quietly on the grid it were violently moved about, the results would be very different; also the difference as between oil and water would vary with the relative mass of the block and the volume of quenching media. But in comparing oils amongst themselves the results are not very different whether the block is moved about or left undisturbed.

LIQUID MIXTURES.

Of the oils in use, according to Thallner,[1] petroleum hardens with greatest intensity; next glycerine, which has heretofore not been sufficiently appreciated as a hardening fluid; then light mineral oils; and finally viscid vegetable oils, for instance, linseed oil. A layer of oil on the surface of water enables a higher degree of hardness to be attained than with oil alone, and a lesser degree of hardness than with water alone. A coating of the oil forms around the tool as it passes through it and retards the cooling effects of the water. The results can be varied by altering the thickness of the layer of oil, but it needs an experienced man, handling comparatively simple tools, to get uniformly good results. With a similar object the water is sometimes mixed with lime or clay, or even soap, all of which tend to form a thin layer of non-conductive material about the steel. A saturated solution of salt is a favourite mixture; its use by file-hardeners is universal, and in some cases quite necessary in order to keep the water fresh. Caustic soda, sulphuric acid, sal ammoniac, sodium carbonate, manganous sulphate, and practically every soluble substance

[1] *Tool Steel*, p. 102.

which comes within reach of the hardening shop has been added at one time or another to the hardening water. These casual additions do little or no harm, and are not costly; they are, however, generally useless.

QUENCHING IN MOLTEN ALLOYS.

As the hardening effect is over as soon as the temperature throughout has been reduced below 680° C., and the rate of subsequent cooling modifies only the tempering effect, it should be possible to arrange the quenching operation in such a manner that hardening and tempering could be accomplished in one and the same liquid. If, for example, it were desired to temper a hardened object back to 350° C., it might be thought that direct quenching in molten lead at that temperature would be equally effective as first hardening in water and then tempering. And so it would if the rate of cooling in the first instance from the quenching temperature down to 350° C. were as rapid in lead as in water. As a matter of fact it is very much slower, and the use of lead or any similar metal, or alloy, or other heated substance is practicable only in comparatively few cases where great toughness and a very moderate degree of hardness is sufficient; in such cases, however, it is both simple and safe.

PRESS HARDENING.

Very much akin to the metal bath is the use of a press for hardening saw blades, band saws, safety razor blades, umbrella ribs, and other articles of thin section. An idea of the general arrangement of such a press [1] is given in Fig. 53, in which *a* and *b* are hollow metal boxes, that can be cooled or heated as desired by circulating water or hot oil through them. The objects to be hardened are pressed, direct from the furnace, between the plates, and when taken out need no tempering, and only rarely require straightening. By grooving the surfaces of the hardening plates any portion of an object—say the back of a hack-saw blade—may be left soft. This kind of press can also be used for hardening coils of thin band steel. For this purpose it is arranged immediately behind the heating furnace into which the coil unwinds. The steel is then pulled through the hardening plates,

[1] Mayers' patent in use at the Remscheid Technical School. Haedicke, *Stahl und Eisen*, 1896, p. 900.

which are previously adjusted to such a temperature and pressure that the band leaves them with the required degree of elasticity. The same object may obviously be accomplished by means of rolls instead of parallel plates.[1]

Very little in the way of general instructions can be given, presuming the tool has been properly heated, as to the manner in which it should be brought into the How to quench

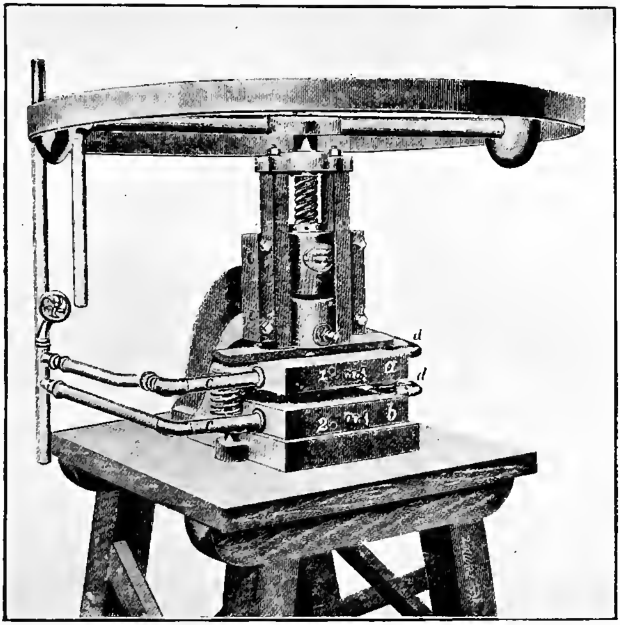


Fig. 53.—Press for hardening thin sheets and strips.

hardening liquid. If it has not been properly heated, no amount of tinkering at the bosh can make up the deficiency; it had better be re-annealed and given a fresh start. Each special form of tool requires individual consideration, and perhaps a few preliminary trials in order to arrive at the mode of cooling least likely to originate dangerous stresses and strains. Great variation in the thickness of the adjacent parts, sharp corners and especially sharp angles are always apt to cause trouble.

[1] Huntsmann Patent, 5781, A.D. 1909.

In this respect the machinist or tool designer and hardener should work together.

The thicker parts of an object should always be the first to touch the water, in order that the force of their contraction may be exerted on the thinner sections whilst they are still warm and able to bend without breaking. It is also advisable to quench all partially heated tools cold end first.

A simple flat bar, if heated uniformly and quenched by steady immersion of a portion only of its length, will invariably be weakened along the sharp line dividing the hardened from the unhardened portion. If the steel is very hard it will frequently crack along the dividing-line either before or soon after removing from the water; or the weakness may not be discovered until the subse-

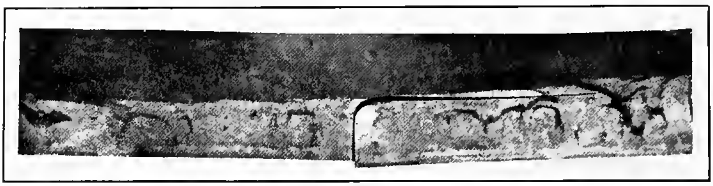


FIG. 54.—Crack between hardened and unhardened portions.

quent grinding starts a small crack. Fig. 54 represents a piece of file steel quenched on the top edge only; after removing from the water the hard edge was, of course, convex, but when it cracked shortly afterwards along the division between the hard and soft parts, it became approximately straight again.

SOFT SPOTS.

A soft spot on the surface of a hardened object is apt to splinter or even cause a deep crack. Such cracks may be originated by handling with cold or wet tongs, by contact with an unevenly heated furnace bottom, by an accidental splash of water, or by being momentarily laid on some cool surface during transit from the furnace to the hardening tank. However such local coolings may arise, if the heat falls below the critical cooling temperature, the area affected will remain soft or harden imperfectly. Consider now the conditions which may lead to the actual rupture. The surface of the object in the

hardened state is permanently expanded; the soft portion is not so expanded and must therefore, so long as it remains a continuous part of the surface, be in a state of tension and actually somewhat stretched. Any sudden shock or molecular disturbance, such as grinding, might cause the tension to overstep the resistance of the softer portion, which, being now free, would contract on itself and leave a distinct break in the surface. An instance of this kind occurring on the surface of a case-hardened disc is shown in Fig. 55, which also, by the file marks, illustrates the relative softness of the splintered portion. Splinters of this kind are generally thicker in the centre, and taper off to a very thin edge; they are also hard on

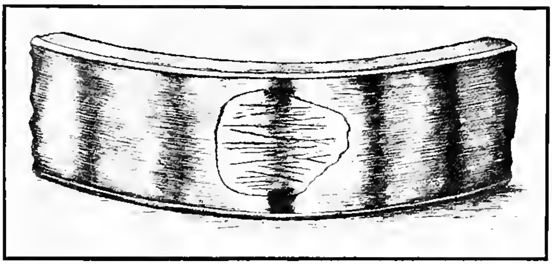


FIG. 55.—Crack on the outer surface of a ring, caused by a soft spot.

the under side. If a section is made through the splinter and properly prepared for microscopic examination, it is usually quite easy to trace its origin back to one or another of the causes mentioned; or, as sometimes happens, to rash grinding.

Soft spots may be due to actual decarburization as explained on p. 52, but they are then very irregular in shape, and not easily confused with those considered in the previous paragraph. They may also be caused by heating the tool in a coal fire which has not first been allowed to burn through. In this case sulphur fumes from the coal combine with the iron, and either form a sulphide of iron, or cause the surface to scale very readily and pit. On this account coke or preferably charcoal, if it is plentiful, is the best kind of solid fuel for hardening furnaces. Whereas the soft spots mentioned in the last

paragraph disappear on rehardening, those caused by decarburization do not, but at the same time they rarely, if ever, cause splintering.

SHARP ANGLES.

The most common cause of cracked tools in a well-regulated hardening shop is sharp angles or corners. However carefully the heating may be done, it cannot overcome the inherent danger; the only remedy is to replace them with fillets and rounded corners of as large a curvature as possible. If sharp angles are unavoidable

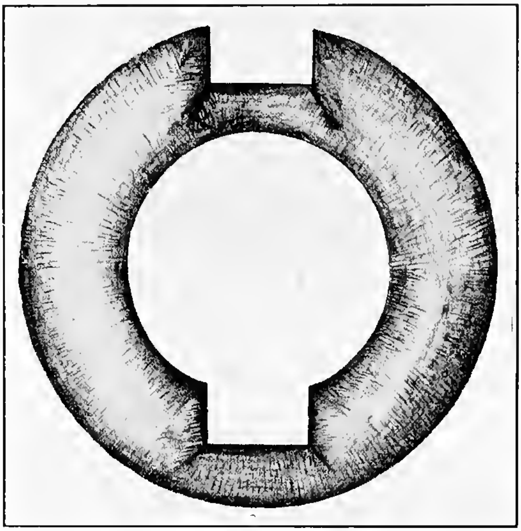


FIG. 56.—Hardening stresses in steel about angles and corners.

the danger may be minimized by filling them with putty, or a mixture of burnt and fresh fireclay made into a paste with soapy water, or sodium silicate. It is also sometimes advisable to reduce the heat of a fillet itself below the hardening temperature by laying in a strand of wetted asbestos for a few seconds before quenching. A well-rounded fillet is, however, better than a great deal of asbestos string, and these other precautions can also be used if necessary.

The cracks which occur at sharp angles are in no way influenced by selective crystallization during quenching, as is sometimes supposed; crystals, in fact, are not

selectively rearranged by the cooled surfaces during quenching, and the direction of the crack being sometimes the same as it would be if they were is a mere coincidence. The cracks are due to straining caused by unequal expansion of the hardened material adjacent to the angle; and they form very easily because the apex of the angle, being sharp, is too small to stretch at all without breaking.

If a ring of steel as represented by Fig. 56 were hardened, its exterior diameter would be increased, and so

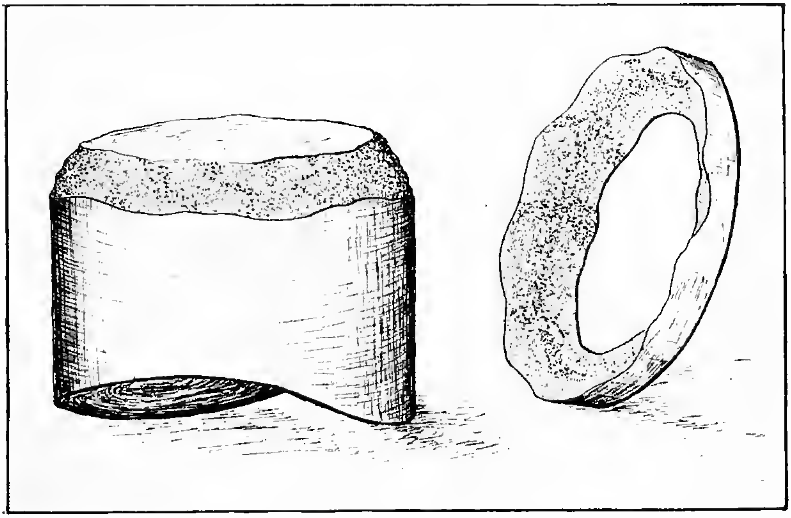


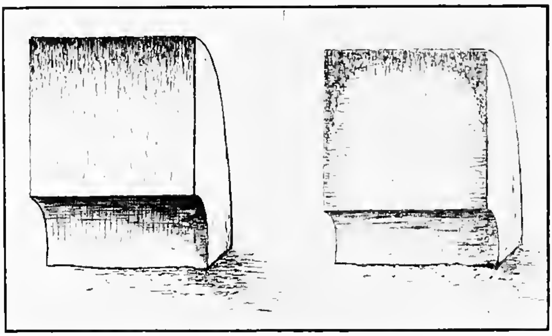
FIG. 57.—Hardening crack around sharp edge due to cooling in directions at right angles to each other.

also would its circumference. The hardening effect would be greater in the shaded parts, and the natural result would be a tendency to pull open the square-cornered gaps, which tendency could be resisted without cracking only if the apex of the square angle were able to stretch sufficiently to correspond to the increased circumference of the ring; and this, the apex being glass hard, it could not do. Similar reasoning would apply if the gap, like a keyway, were on the inside, and the internal diameter, as sometimes happens, were to contract, except that the gap would be acted upon by compressing instead of extending forces.

SHARP CORNERS.

We have already referred to the tendency of steel to fracture along a line sharply dividing the hardened from the unhardened portion of a bar. If the section is sufficiently large there is always some point in the interior of a bar where this condition, to some extent, prevails. It is particularly objectionable where surfaces meet to form a sharp corner, and special precautions must be taken with very hard steels to prevent actual breakage. A round bar of tool steel with flat ends if heated and plunged in water may shed the edges in the form of a complete ring (see Fig. 57).

A great many solid gudgeon pins of the kind formerly



FIGS. 58*a* and 58*b*.—Two ways of arranging cooling stresses in the teeth of cutters.

used have met this fate. Here, again, the safest way out of the difficulty would be to modify the design. If that is not possible, and only either the round surface or the end requires to be hardened, then the rapid cooling should be confined to these surfaces; this can be accomplished by means of a spray arranged to strike the end, only, or the curved surface.

Similar considerations account for the flaking of hammer faces, and the corners of roll turner's tools. If overheating and irregular distribution of heat are added to the inherent danger, then little short of a miracle can avert failure. The circular fracture with which the teeth of milling cutters sometimes break off is due to a similar cause, and may be avoided by laying a circular plate,

extending beyond the teeth, on each side of the cutter, so that the cooling may operate only at right angles to the axis of the cutter and produce an even depth of

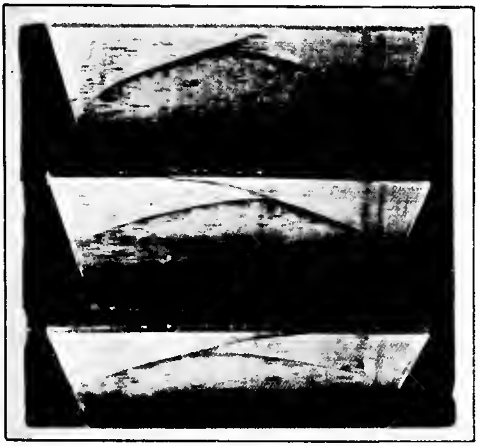


FIG. 59.—Stress cracks on teeth of cutter.

hardness across the width (Fig. 58*a*), instead of a curved line dividing the hardened from the unhardened portions, as in Fig. 58*b*. Cracks of the kind referred to are illustrated in Fig. 59 on the teeth of an actual cutter.

IX

TEMPERING AND STRAIGHTENING

THE object of tempering may be either to avoid hardening cracks, or to reduce brittleness to a degree compatible with certain mechanical processes. That tempering may, under certain circumstances, originate cracks, is a proposition not readily accepted, but that it actually does so is suggested on p. 127.

TEMPERING COLOURS. Although a comparison of the actual temperatures to which "dark red," "cherry red," "bright cherry," and so on are supposed to correspond will show variations amounting to 100° C. or more, there is, on the other hand, a fair agreement between authorities as to the temperature at which the different colours appear when a piece of bright steel is heated. The following are the figures usually given in the text-books, journals and engineering pocket-books—

Colours.	Temperatures.
Light straw	220° to 230° C.
Dark ,,	240° C.
Yellowish-brown	255° C.
Reddish-brown	265° C.
Purple	275° C.
Violet	285° C.
Cornflower-blue	295° C.
Pale blue	310° to 315° C.
Sea-green (or grey)	330° C.

It is, however, erroneous to suppose, as is general, that these colours reliably represent certain fixed temperatures. It is doubtful even whether they represent definite degrees of tempering. Opinion is divided on this latter point.

If a piece of polished steel weighing, say, five grams were placed in a vessel previously heated and kept at 275° C. it would become yellow after two minutes and pass through every colour up to light blue in about half an hour. In this way, similar pieces of steel were heated with free access of air at varying temperatures with the following results, the figures being minutes required to produce the full colour stated at the head of the vertical columns— TIME ELEMENT.

Temperature.	Straw.	Brown.	Purple.	Dark blue.	Pale blue.
200° C.	6	49	—	—	—
220° C.	3	33	63	—	—
250° C.	1	10	39	—	—
275° C.	½	3	11	27	40

From these results it appears that if the tempering effect—not the colour—depends on the temperature, and is mostly independent of the time, then the colour is of value only as an empirical guide under definite conditions. It has been said that the result would be the same, in respect to both hardness and other properties, whether the colour were obtained by a shorter heating at a higher temperature or a longer heating at a lower one. This, to say the least, is a very doubtful conclusion, and is certainly not borne out by mechanical tests on oil-hardened and tempered motor-car steels, which, after tempering for periods varying from fifteen minutes to two hours, show no very great differences.

The temper colour, as was shown by Humphry Davy in 1813 or earlier, is due to surface oxidation,[1] and it might be expected to change in colour with time independently of increased temperature, just as scale formed at red-heat increases in thickness in time, although the temperature remains constant. Under such conditions, both the temper colour in the lower ranges and the scale formed above red-heat may be very misleading tempera-

[1] See paper by Turner (*Chem. News*, 1889, vol. lx. p. 190), who says, "A purple can be produced at 250° C. in a few minutes, which would require an hour at 220°, and about twelve hours at 170°, though the ultimate result would be the same in each case.

ture indicators. It would, however, be generally conceded that the actual temperature, and not the incidental thickness or colour of the scale, determined the extent to which certain physical changes had taken place. The rate at which the colours are formed at any fixed temperature is increased locally about any portion of a piece in actual contact with another metal; say the end of a naked thermo-couple.

TRADE CONSIDERATIONS.

In certain branches of trade, tools come on to the market "blue-finished," and would hardly be saleable otherwise. For such reasons, and in view of its general convenience, the temper colour is likely to continue, and may even be recommended under definite conditions, to decide when the required degree of tempering has been reached. It is also quite indispensable under some circumstances in hardening simple forms of tools which, after being partially quenched, are rapidly brightened and allowed to run back with the inside heat until the selected colour appears.

OIL AND LEAD BATHS.

For accurate work, however, colour indications are decidedly inferior to an oil bath which can be maintained for any length of time at a fixed temperature. Articles heated in oil can be raised to the same uniform temperature throughout, which is a consideration of some importance. For higher temperatures a lead bath may be used, and, in the form of a rectangular trough, is especially suitable for tempering long blades. Lead is also used everywhere for tempering file tangs, drill shanks, and other parts of tools which require to be locally softened. The lead bath can easily be kept slightly above its melting-point (327° C.) by observing the crust of metal which forms on the sides of the trough. The bath can be kept fluid at lower temperatures by adding tin in the following proportion—

Per cent. tin . .	10	20	30	40	50	60
Fluid at	300°	275°	255°	230°	210°	185° C.

Or by adding antimony (which is cheaper than tin) in the following proportions—

Per cent. antimony . .	5	10	13
Fluid at	290°	270°	250° C.

Higher temperatures are roughly controlled by the charring (300) or sparking (430) of a strip of pinewood, or the rate at which temper colours form and creep up the length of a bright steel bar immersed vertically in the bath. All these methods are inferior to actual pyrometric measurements, but often sufficiently accurate and much more practicable.

Small articles which are manufactured in large quantities are sometimes tempered after oil-hardening by heating until the adhering oil flares or its flame dies down. This method cannot be commended if the pieces are of irregular thickness, because the thinner parts are more quickly heated to a higher temperature. In other cases, with split washers for example, the method appears to give excellent results. It is generally called for when temperatures beyond the safe usage of oil baths are required. OIL FLARING.

It sometimes happens accidentally that a steel suitable for turning tools or small drills gets made up into machine taps or some such tool required to withstand rough usage. With the usual degree of tempering they are too brittle; and appear too brittle after further tempering until they become too soft to keep a cutting edge. This brittleness is caused by free cementite, which is not affected by tempering, though the net brittleness decreases, and finally the mass of material can neither cut itself nor hold the cementite particles up to the work. The remedy is to choose a milder steel and temper it to a less degree.

The table on p. 108 is usually accompanied, in an additional column on the right hand, with a list of tools which should be tempered to the respective colours. Such lists are apt to be misleading, unless the kind of steel used, the size of the tool, the manner of hardening it, and the precise kind of work for which it will be used are specified. Every machinist prefers the most durable tool he can get, and on that account draws the temper no more than may be necessary, and as often as not to some colour quite different to the one stated in the usual list. In the matter of tempering, a few trials

under working conditions are always more satisfactory than a stereotyped procedure taken from a book or a catalogue. The latter method will always give passable results, but a long way below the best results obtainable. If during the tempering operation the object has also to be straightened, then the temperatures used may have to be increased beyond what would otherwise be necessary.

STRAIGHTENING. Warping in tools may be due either to want of uniformity in mechanical structure or rate of heating or cooling. Those due to mechanical strains (Fig. 34) or irregular forging, can be improved by annealing and slow cooling; those due to irregular heating or cooling must be remedied if they cannot be avoided, and frequently the former is found least troublesome in the long run.

SETTING TOOLS. In tools of irregular thickness, but symmetrical cross-section, warping may be almost eliminated by setting the tool out of the straight in such a manner that quenching always pulls it back again. The handling of a long sword-blade may be cited by way of illustration. The blade, which has been already annealed to remove forging and rolling stresses, is heated to redness in a salt bath or on the hearth of a long furnace. It is then brought out on to a metal table, where, the point being held in a slot, the entire blade is bent about its back edge to a fixed template. The template is constructed of such a form as experience has shown will bring the blade out straight with a certain method of quenching, which is purposely made as simple as possible, so that it can be easily repeated any number of times without deviation. All half-round files are set before hardening, and then straightened slightly if necessary after quenching, but before they are quite cold. For this purpose a pair of iron bars are fixed at a convenient distance apart on the top of the tank, the file is strained in the required direction between them, and water is thrown on the upper side of the file to make it quite cold before the stress is relieved.

SPECIAL SHAPES. Steel sheets, such as saw blades, are best hardened if possible in a press (Fig. 53), which keeps them so straight that very little, if any, smithing is required.

After direct quenching most of the buckling can be taken out by passing them between the polished flat surfaces of a press, which are heated to the required tempering temperature. The final straightening is then done with a hammer, the length of whose rounded face runs nearly parallel to the shaft, in a manner which, though apparently simple, requires great skill in order that each blow may actually straighten and not make the steel more crooked. Each blow is intended to stretch the concave surface of the steel, and is made to do so in the required direction by varying the direction of the indent made by the hammer face. Material which cannot be stretched cannot be straightened by the indent of a hammer face. This means that saws or machine knives, which are made very hard, can be readily cracked in the smithing operation, because the nature of the material does not permit it to extend as much as is required. Small hair cracks on the surface of metal-cutting saws, which become visible only on grinding, or perhaps later, can frequently be traced directly to the indent of the smith's hammer.

Long tools, such as drills and reamers, after being warmed are straightened under a screw press. Long thin blades, such as sword-blades, are laid in a slot or a pair of slots, and straightened by means of a claw; *i. e.* a stiff piece of steel with a slit of suitable width at the end. A couple of claws may sometimes be used to straighten a blade by twisting each end in opposite directions, the blade having, of course, been previously brought to the required tempering heat; or one end may be clamped in a vice. Every precaution should be taken to avoid warping in the first instance, as a straightened article will more easily run out of truth at any subsequent time under rough usage.

X

HARDENING TYPICAL TOOLS

CHISELS, SATES, MILL-PICKS, ETC.

IN hardening such objects as chisels and sates, it is not necessary to heat the entire tool, but merely one or two inches of the pointed end. Too short a portion should not be heated, otherwise the part behind the hardened point may bend under heavy blows, and cause the extreme end which cannot follow the deflection to break. If a great number of chisels have to be hardened, an ordinary reverberatory hearth, with the heat passing from the fire at one end to the flue against the working door at the other, does very well for heating purposes. The tools may be packed into a short piece of iron piping six or eight inches in diameter, open at both ends, and rolled gradually towards the position on the hearth where the temperature, as indicated by "Sentinels," or other means, is beyond 770° C. and not 800° C. (see Fig. 60), or they may be reared in rows over a piece of one-inch square iron. As the points are towards the fire they only are heated to the required hardening temperature. At small expense the entire batch of tools is prepared for quenching, which operation can be accomplished almost as rapidly as the tools can be conveyed singly from the furnace to the hardening tank.

A salt or lead bath furnace can also be conveniently used for hardening chisels. The latter is especially suited for hardening millpicks, as one end at a time can be easily heated without interfering with the temperature of the other end. Tempering is done by laying the shanks of the chisels across the breadth of a long narrow stove where they are heated up uniformly until the dark blue or some other chosen temper colour appears on the brightened point. A piece of **U** angle iron can be

readily made into a suitable stove, heated either by gas or otherwise. Hand chisels for chipping very soft materials are sometimes made from steel containing about 0·4 per cent. carbon, in which case they should be hardened from 800° to 820° C., and need not be tempered.

RIVETING SNAPS.

These tools are usually machined direct from the bar. If the steel has a coarse fracture instead of the normally fine one it is unfit for first-rate snaps, and a tool made from it is almost sure to break in the groove, even if the cup stands well. The aim should be to form an even layer of hardened steel immediately behind the face of

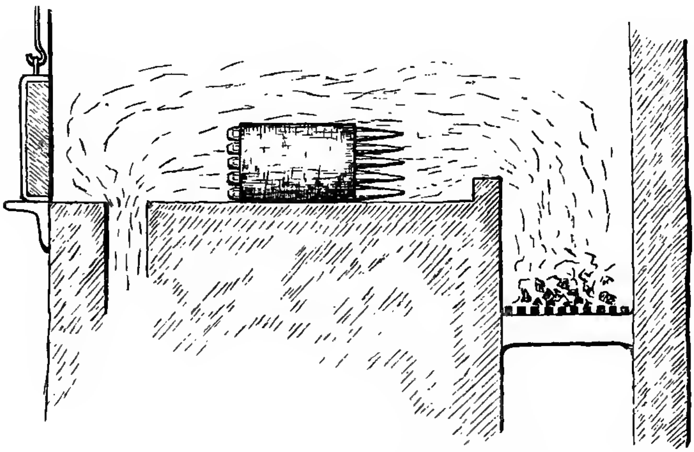


FIG. 60.—Reverberatory hardening furnace.

the cup. Direct quenching would make the edges too hard, and leave the centre of the cup too soft, and the former would tend to fly off in use. The snaps can be well hardened under a tap, as shown in Fig. 61, A, but an equally convenient way is indicated by Fig. 61, B.

The snaps may be heated like chisels in a parcel, and can also be tempered like chisels, or, better still, by placing them shank end first through the perforated cover of a shallow lead bath until the correct temper colour appears.[1] When large quantities are being hard-

[1] Although a temper colour corresponds to different temperatures under different conditions, as stated on p. 109, it answers to the same temperature if the conditions are kept the same.

ened, a spring clip can be arranged so that the hot snap is held in the correct position over the ascending water-jet, and can be easily knocked out and replaced by its successor.

The life of well-hardened chisels, sates, and snaps, is as often shortened by wear in the head as fracture at the point. This wear is very pronounced if the tools are made from annealed stock. Amongst other ways, it can be avoided by hardening the heads, say in oil, before the cutting edge is hardened. During the second heating, if carried out as suggested above, the head gets heated

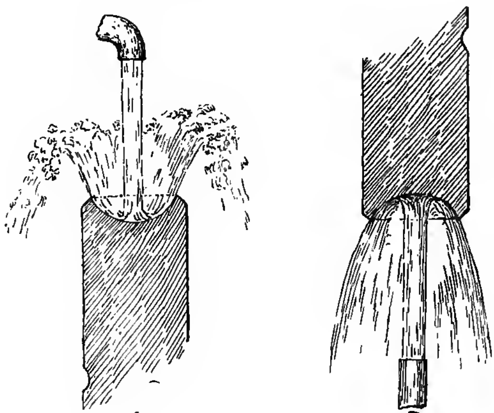


FIG. 61.—Methods of hardening boiler-maker's snaps.

only to 600° to 700° C., and when cold has as good an elongation as before, but a much higher elastic limit, and hence neither splits nor so readily forms a mushroom head.

TAPS, REAMERS, BROACHES, ETC.

The hardening of taps and such tools as reamers and broaches should bestow on them hard cutting edges to stand up to their work, and comparatively soft flexible cores and flutes, so that accidental shocks in a deep hole may not cause them to break off short. This ideal can be approached in two ways. First, by the use of good crucible steel free from non-metallic impurities and low in manganese, which from its nature will permit the hardening effect to penetrate barely beyond the bottom of the teeth; and second, by a mode

of quenching which, on account of its general applicability, deserves a detailed description.

Broken hardening. In hardening any form of toothed tool, so that the hardening effect barely penetrates to the root of the teeth, we not only prolong the life of the tool, but also minimize the danger of water cracks. The operation known as "broken hardening" consists in quenching the tool in water until the colour has disappeared from the surface, and then allowing it to stand quietly in oil until it is cold. The heat still remaining in the centre of the tool keeps it soft and penetrates gradually towards the edges of the teeth, but it can at most only slightly temper them up to the heat of the surrounding oil. Tools may be safely hardened in this manner which by quenching outright would frequently crack. Working continuously on the same kind of tool, the operator quickly learns just how long it is best to cool in water, so that after oiling no subsequent tempering is required.

A similar result can be attained in the hardening of reamers, taps, etc., by heating them in a lead or salt bath until the teeth only are red, and then quenching, but the results are not so reliable. It is, of course, much easier to correct warping in tools which are left with the core soft.

Milling cutters and rolls. Milling cutters should also be quenched, first in water until the teeth lose their colour, and then in oil. Sharp angles in keyways and at the root of the teeth should be avoided for reasons stated on p. 104. If teeth break off at all they generally do so along half-moon cracks, and either because they have been overheated or badly quenched, or both. Very large cutters may be handled like steel rolls. The following description of the hardening of a steel roll is taken verbatim from Thallner's book.

"The danger of cracking from the interior has been reduced in the construction of the roll by boring it out. The entire surface of the roll *a-a*, *b-b*, Fig. 62, is to be hard, while the journals, *z-z*, are to remain as soft and tough as possible.

"Previous to heating, the journals, *z-z*, are given a coat of loam, or clay, which, to make it more binding,

is mixed with cows' hair, and, to prevent peeling off in consequence of shrinkage by heating, with chamotte, graphite, pulverized firebrick, etc. Each journal is enclosed in a sheet-iron pipe of as large a diameter as the thickest part of the roll, and the mixture rammed in between the pipe and the journal. At *m-m* discs of sheet-iron projecting beyond the edge of the roll are arranged. Finally the bore, the ends of which are provided with

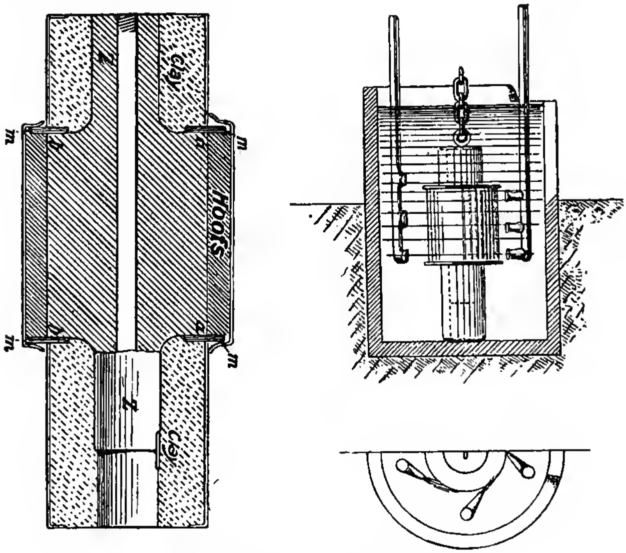


FIG. 62.—Appliance for hardening rolls.

screw threads, is up to the latter rammed full of dry loam.

" In heating the roll, which frequently requires several hours, it must be borne in mind that during this time the surface is exposed to the injurious effects of the gases of combustion, as well as to decarburization, if suitable protection is not provided. For this purpose the roll is enclosed in a sheet-iron pipe of somewhat larger diameter, and after the space between the roll and the pipe has been rammed full of hoof-shavings, or charcoal, the edges of the pipe are turned in.

" The roll may now be brought into the least heated part of a reverberatory furnace of sufficient width and

allowed slowly to heat. Heating in a reverberatory furnace is preferable, because other appliances, for instance heating with charcoal, are not always available, if the roll has to be turned to attain a uniform temperature. The reverberatory furnace used should have as long a hearth as possible, so as to cause a heat gradually increasing towards the fire grate. The roll is now gradually rolled into the higher heat and turned, more frequently the hotter it becomes. When the roll is supposed to have acquired the suitable hardening temperature, a hook is screwed in the threads on the end of the journal, and the roll is suspended by it by means of a chain. It is then freed from the sheet-iron discs, which can be readily removed, and quickly cleansed from adhering hoof-shavings with a wire brush. The roll is then plunged into the hardening bath, which should be located near the furnace.

"Since uniform cooling of a roll of large diameter by moving it about in water is impossible, it is allowed to rest whilst the water is brought into vigorous motion. This object is attained by the appliance shown in the illustration. It consists of a vessel of sufficient depth, and of a diameter twice or four times as large as that of the roll, and is provided with pipe conduits for the introduction in a slanting direction of water under pressure.

"The nozzles of the pipes are made broad and slit-shaped, and a number of them are distributed at various heights, so that the water around the roll is set in a vigorously whirling motion. The manner of using this appliance will be readily understood from Fig. 62."

Hollow tools.

On tools having a smooth narrow bore which requires to be hardened, an asbestos washer should be laid after the heating operation, and against this washer should be pressed the flange end of a pipe, delivering a stream of water sufficient to fill the bore. If the bore is wide enough, a piece of gas piping closed at one end and perforated may be passed through the tool so that forcible streams of water, coming through the perforations in the pipe, strike the parts to be hardened. Narrow

parts, as, for example, the path in a ball race, may also be spray-hardened, as indicated by Fig. 63.

As ball races are now frequently made from case-hardened mild steel, they are generally quenched outright, either vertically on a hook, or horizontally on a piece of stout wire whose lower end is coiled into a circle round about and at right angles to its length. They may also be quenched on an arbor in order to preserve their shape, in which case the arbor should be designed

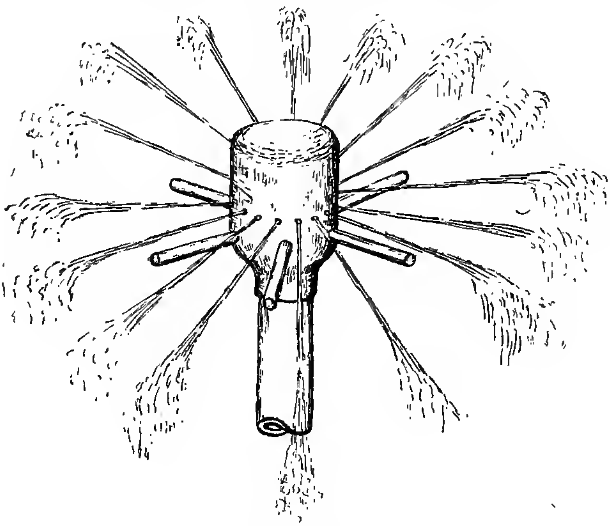


FIG. 63.—Arrangement for hardening the inside of narrow rings.

to interfere as little as possible with rapid and uniform cooling.

RAZORS, TABLE-BLADES, AND PEN-KNIVES.

Knife-blades are frequently heated in a slow coke or charcoal fire, but a shallow salt bath containing a movable basket is a more ideal arrangement. The heated blades are quenched by being pulled almost horizontally through the water with the thick end first. Table-blades can be tempered in bulk in an oil bath, and pen-blades by laying their backs in molten lead, or on a hot plate, or even, when handled on a small scale, in the flame of a spirit-lamp until a suitable colour runs down to the edge. Generally, however, the blades require to be straightened singly, and the usual method is to temper them immedi-

ately after hardening, and at the same heat to straighten them.

Long coils of thin steel are heated for hardening by passing at a suitable rate through a tube which extends between the opposite walls of a furnace. On reaching the exit end the steel should have already reached the hardening temperature, and passes then through an oil tank, and, subsequently, in a continuous line through a tempering furnace or lead pot, or sometimes first through a pair of brightening rolls, and then through the tempering-tube, so as to give a finished spring the usual blue colour. This operation is similarly applied to wire. If the steel wire is high in manganese and not too thick, it acquires high tensile properties simply on passing from the hardening furnace through the air on to the coiling machine; but the other mechanical properties of the wire, *i. e.* the elastic limit, reduction of area, etc., are not so good as in material which has been oil-hardened and tempered.

WIRE AND WATCH-SPRINGS.

Fine wire is hardened and tempered and at the same time kept bright by passing it over a gas-pipe, through the upper part of which issues a large number of small bunsen flames; thence it passes through an adjacent trough filled with oil in constant circulation, and finally through a hot lead bath. The bunsen flames may be replaced by two poles connected with a suitable source of electric current; the wire between the two poles is protected from oxidation by passing through a tube at the entrance end of which a luminous gas flame is kept burning.

SAWS.

Hacksaws are usually hardened from a salt bath. A dozen or more at a time are hung vertically on the outer edge of a ring from which small hooks are projecting, and in this way they are held in the salt bath and quenched in an oil tank. For tempering they are laid with their flat surfaces together in a shallow frame, pressed straight and well home by means of clamping screws, and in that form submitted to the re-heating process. Larger saws, such as Russian crosscuts, may be tempered in large batches in a similar manner by heating in a salt mixture which is fluid at all temperatures above, say, 200° C.

When tempered in this way under great pressure even large saws are nearly straight and require little or no smithing.

Hacksaws with flexible backs are hardened singly. The ends are attached to the respective jaws of a pair of tongs which widen and keep the saw-blades rigid when the handles of the tongs are gripped. In this condition the toothed edge is moved backwards and forwards along a line of bunsen flame issuing from a long fine slit on the upper surface of a metal box. The teeth only become red hot, and are hardened by oil quenching. Under manufacturing conditions this apparently difficult operation is done with amazing rapidity.

HAMMERS AND ANVILS.

Small hand hammers are heated throughout by any suitable means, taken from the furnace, and drawn with a sharp sweep through the hardening tank. They are then, being still quite red, hung by means of the hole on to a projecting peg so that the lower face is below the surface of the water, and the upper face is in direct line with a smooth stream of water falling from a tap. For special forms, engineers' hammers, for example, the round-nosed end may dip into a small hemispherical basin through which fresh water is continually rising, whilst the upper flat face meets a stream of water falling from a tap directly above it. The two faces of small hammers may also be expeditiously hardened separately by heating in a lead bath. Larger hammers can be treated in the same way, but it is economical to pre-heat them somewhat in a reverberatory furnace.

Large sledge hammers are most easily hardened between two horizontal sprays. The heated tool is laid, with the eye standing vertical, on a small metal block between the sprays (Fig. 64). A strong stream of water is suddenly turned on and quickly cools the two faces, whereas the middle of the hammer about the eye remains quite soft: whilst still sufficient heat remains, the water is stopped and the ends of the hammer brightened in time to observe the required temper colour, after which the hammer is cooled outright. Sledge hammers made from mild steel do not require tempering. The faces of

a large hammer can be hardened in an ordinary bosh fed with a single water-tap as follows: The heated hammer is gripped firmly about the middle with a pair of tongs, and swung length on through the bosh and back again. One end is then for a few seconds held under the tap whilst the other dips into the water. The hammer is then deftly turned and swung again through the bosh, and again held, but this time with the other end under the tap, and so on, according to its size, the

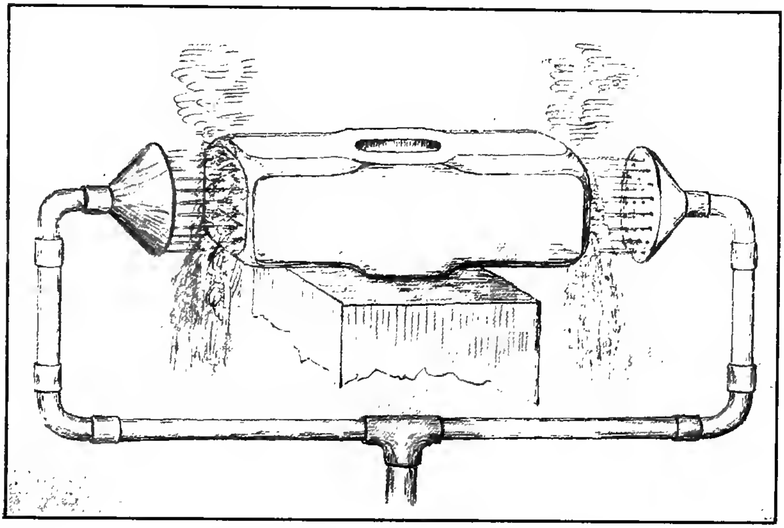


FIG. 64.—Method of hardening sledge-hammers.

hammer is swung three or four times or more until the faces are nearly cold.

Anvils which require hardening on the face only may be heated in a lead bath face downwards, then supported, also face downwards, on a grid or across two triangular pieces of steel in the water tank directly over a stream of cold water ascending through a spray. The anvil should be immersed as far as the hardening heat extends, otherwise the corners may crack. The hardened face, if made too thin, will crack and shell under the blows of the hammer. Blacksmiths' anvils and similar flat faces terminating in sharp edges and corners are best hardened with a powerful spray.

DROP-FORGING DIES.

The hardening of drop-forging dies for producing intricate objects requires the exercise of considerable experience and more skill than can be assimilated from a written description. In many cases the bane of the steel-hardener—sharp angles and corners—cannot be avoided. In all save the simplest forms the die should be withdrawn from the water before it is quite cold, be brightened on the surface, and tempered by the heat still remaining in the massive unquenched back. As a matter of experience it is found that certain parts of any particular die will be most disposed to spring off or develop subsequent cracks. It may be necessary to temper these parts to a greater extent by laying on them pieces of heated iron or otherwise. In the same way certain other parts of the die may require additional cooling by the local application of a limited amount of oil or water. If the dies are heated for hardening in a reverberatory or muffle furnace the faces should be covered with charcoal or otherwise protected from oxidation. If this is not done, the extreme surface remains soft though the die is quite hard immediately underneath.

XI

DEFECTIVE TOOLS

It is easy enough to spin fine theories about the origin of defects in tools, and not altogether a bad thing to do, so long as the theories are taken for what they are until observation and experiment confirm them or otherwise. The characteristics of a broken tool from which the causes must be deduced can generally be neither measured nor weighed, and yet are quite as convincing as absolute figures of quality would be, and much easier to interpret than some kinds of figures are. A quick sense of the meaning of apparent trifles and close observation and comparison of appearances are important for the tool-hardener who would manage the forces he deals with, just as they were for the steelmaker of the last generation but one, who controlled both his raw materials and finished bars by appearances, and thereby to some extent earned the right he exercised as an authority, not only on the manufacture of steel but also on its uses and properties and the causes of failures and defects.

Cracks.

It is not uncommon to attribute all cracks to overheating or some other abuse of hardening methods. They may, however, be due entirely to the size and shape of the object, or to unsuitable composition of the steel from which they are made. Fig. 65 A and B are intended to represent the appearance of the same kind of steel quenched in each case from the same temperature and varying only in cross-sectional area.

A has cooled so rapidly that the characteristic appearance of hardened steel extends throughout. B shows a marked core of unhardened steel. It is evident that a larger section would possess in a still more marked degree

a core which, owing to a slower rate of cooling in the interior of the bar, would not be appreciably harder than a piece of steel as forged.

It may, we think, be presumed that the greater hardness of the exterior portion of a quenched steel bar is accompanied by a greater degree of permanent expansion. From the surface towards the centre the expansion would decrease with the hardness if the interior portions were free to arrange themselves as they chose. They are, however, attached to the hard unyielding and

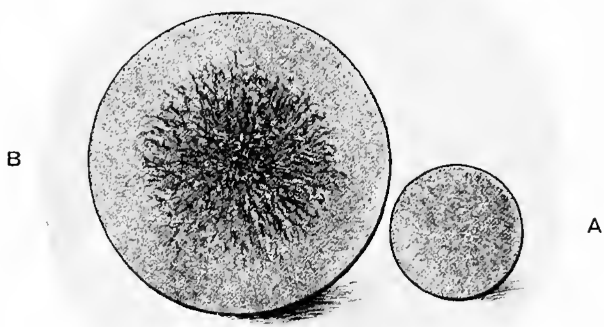


Fig. 65.—Soft core in hardened steel.

permanently expanded exterior portions, and must therefore remain in a state of tension and actually stretched as long as the hardened object is intact.[1] If, however, the strain should exceed the endurance of the steel a crack is formed internally, and those steels which are naturally less extensible are the more apt to crack in this manner.

[1] When working on large forged objects which have to be accurately finished, the machinist frequently finds that the marked dimensions vary appreciably after rough turning; that is to say, after the stressed surface has been removed the internal material is free to assume its normal shape.

TEMPERING CRACKS.

From the above considerations it is clear that any internal defect in the steel itself, such as a pipe, a crushed centre, an imperfectly welded blow-hole or segragation would cause premature fracture very much like a slag streak does in a tensile test-piece cut transversely. It also follows that any change which increases the expansion of the exterior portion without at the same time decreasing its rigidity, increases the strain of the internal portions and may cause them to break apart. In this way a bar which in the hardened state was perfectly sound may, on tempering, develop internal cracks unless heated very slowly.[1]

A large number of pieces about one and a half inches square were cut from an annular ring, then turned to one and a half inches round and all hardened and tempered alike in a manner which would be generally considered correct. Every piece appeared perfectly sound after hardening, and some of them also after tempering; but on turning the apparently sound ones to a smaller diameter for testing purposes they also showed longitudinal cracks at right angles to each other. The appearance of the broken pieces is reproduced in Fig. 66, and might easily be considered sufficient evidence of unsound steel.

A similar number of pieces from the same ring were hardened and tempered before turning off the corners, and produced perfect test-pieces free from any sign of cracks. In both series the mechanical properties of the hardened material were practically the same, save the reduction of area, which in the split pieces was naturally much less.

Had the same treatment been given to round bars of the same material whose diameter was much smaller or much larger, the danger of internal cracks on either hardening or tempering would have been more remote.

From the above considerations one might be led to the conclusion that merely so far as sound bars are con-

[1] The phenomenon of "clinking" in large ingots, particularly in those of circular section and hard material, is well known and due to similar causes.

cerned a degree of overheating, *i. e.* the penetration of the hardening effect and consequent expansion to the centre, might sometimes be advantageous. This statement is not intended to provide an apology for neglect of any kind, but rather to suggest that, with a given material, it may be necessary to consciously depart from

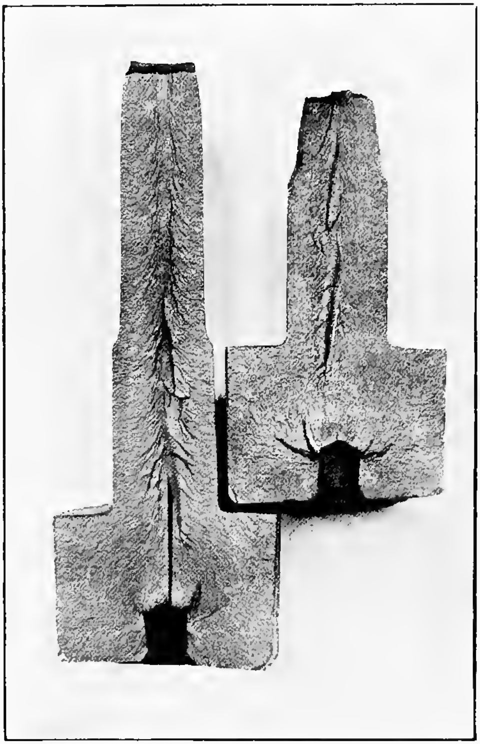


FIG. 66.—Test pieces cracked by tempering.

an ideal to keep down the percentage of wasters. There are also reasons to suppose that cracking in particular kinds of steel made into special shapes is more apt to occur when hardening is done from certain temperatures than when either higher or lower temperatures are used.

INTERRUPTED COOLING.

Partially cooled steel objects will sometimes break on taking from the quenching bath which would remain sound if left in the bath until they were quite cold.

Very likely reasons for this behaviour, which is well marked only with objects of certain shapes, are as follows—

(1) That the inside portion has not yet passed the critical expansion period (see p. 83 and Fig. 49), and this is partly suppressed by keeping the object in the water.

(2) The outside expands under the warmth of the heat diffused from the inside, and so pulls the centre apart.

Under conditions described in (1) the crack would originate on the outside, and under conditions (2) on the inside; if both act together the tool would probably break with explosive violence into several pieces.

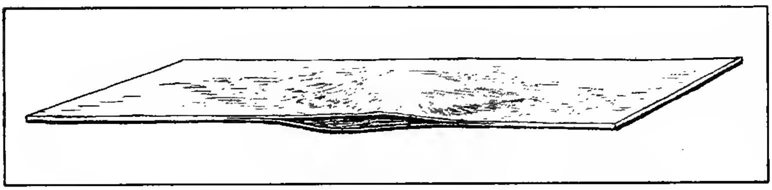


FIG. 67.—Piece of flat steel containing pipe; after hardening.

GEOMETRICAL CONSIDERATIONS.

The difference may be much less between a bar that cracks and a similar one that does not than the differences which exist amongst a number of uncracked bars. Tools indistinguishable from one another may pass from the shop only one straw or a thousand straws removed from breaking-down point. But the danger of internal flaws, either actual or potential, is always greatest in complete round sections. In the first place, because the strains are symmetrical and all converge on to the centre; and in the second place, because (in tempering) the heat is equally distributed, and the expansion therefore is comparatively large before any portion of the rigid surface is hot enough to become plastic. In a square bar the corners quickly attain the heat of the tempering bath and can yield to internal stresses before the surface expansion produces rupture; moreover, under like conditions the centre of flat surfaces can yield better than any part of a circular section. Flat pieces are still less

apt to break in this manner, even if they are very thick and never if they are thin, unless the steel is defective. Thin blades which are made from sheets or strips containing a pipe, a slag inclusion, or an unwelded blow-hole will frequently open out as indicated by Fig. 67.

STRAIGHT CRACKS.

The kind of path along which a crack travels may be almost conclusive evidence of its origin. No experienced person would ever suggest that the half-moon or thumbnail cracks met with in chisels, plane irons, cutter teeth,

FIG. 68.—Forked crack following cementite outline (magnified 100 diameters).

and so on were due to defective material. They might be due to unsuitable material, overheating, careless quenching, or some other mistake discoverable on closer observation. Cracks of this kind, and practically every other which originate from hardening strains pure and simple, sweep along a smooth path, from the curvature of which some indication of the mode of heating or the manner of quenching can generally be deduced. On the other hand, a crack which forks irregularly, though the effect of overheating or other errors may appear, is usually traceable to free cementite, or cold working, or both.

A crack runs by preference along the path outlined by free cementite, because cementite is brittle and offers little resistance; and also because the different degree of expansion of cementite and the material in which it lies embedded favours the origin as well as the extension of a crack. Figs. 68 and 31 are typical examples. In this must also be included such cracks as may originate in, or traverse the path occupied by, slag inclusions. Microscopic examination and the knowledge of the composition of the steel enables us to detect these causes when they exist. Heavy cold-working through the blue-brittle stage (p. 56) or crushing between rolls or otherwise may originate forked cracks in steel which contains FORKED CRACKS.

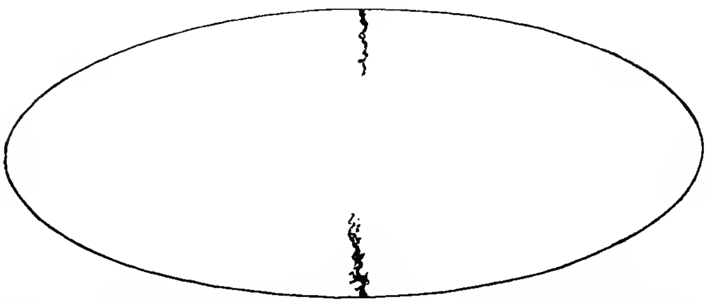


FIG. 69.—Cracks in symmetrical objects due to crushing between rolls.

neither slag streaks nor free cementite. They are not usually visible until after hardening, and then appear in many cases on opposite sides of the crushed object, as represented diagrammatically by Fig. 69.

A crack may be so fine as to elude detection at the time the tool is hardened and become visible after lying about for some days or weeks. Such cracks may easily be detected in sand-blasted articles if, before cleaning, they are placed for some hours in oil, or happen to have been oil-tempered, by the oil which has penetrated the crack again oozing out and making a dark stain on the matt-silver surface. On a water-quenched tool, or even an oil-quenched tool which has been cooled off in water after tempering, or subsequently been ground on a wet stone, the crack may be gradually widened by the oxida- INVISIBLE CRACKS.

tion of its moist surfaces. As the oxidized metal occupies a larger volume, it either presses the faces of the crack apart or forces its way between them on to the surface. Fig. 70 is an example of such a crack originated by cold working in the threaded hole of a boiler-plate firebox, and Fig. 71 a similar crack occurring in an oil-hardened blade.

FIG. 70.—Crack in threaded hole of boiler-plate fire-box.

FIG. 71.—Crack on bevelled edge of sword-blade.

The nature of the material exuding from such cracks in oil-hardened steel may be some indication as to whether the crack originated during the quenching or in some subsequent operation.

GRINDING CRACKS.

A piece of quenched steel characterized by great hardness is sometimes spoken of as being " glass hard "; it should be remembered that on the hardest parts it is also nearly as brittle as glass. A brittle object is readily broken because a blow is an effort to change its shape which strains it more in one part than another. But

heat also can change the shape of an object, *i. e.* cause it to expand. If a hardened piece of steel in the form of a long rod be clamped at one end in a horizontal position so that its free end rests in front of a divided scale, and the tip of a spirit-lamp be brought for a moment under the rod near the clamped end, then the free end, owing to the expansion of the underside, will move up the scale. This experiment [1] shows that a piece of the hardest steel bends *slightly* under the influence of local heating without fracture; but if the heating be strong and the local expansion suddenly great, then the steel, like glass, will crack. This is what may happen when a piece of hardened steel is rashly brought on to a sharp dry emery wheel.

The danger is not so great with ordinary carbon steel, because the rise in temperature is quickly followed by a softening of the material. But high-speed steel remains hard and inflexible at much higher temperatures, and the risk of fracture is therefore greater. In the latter case a small crack once formed readily extends further and deeper if an attempt is made to grind it out on an emery wheel. Cracks can be readily ground out of annealed material, and the steel may be handled in all respects with greater freedom.

OVERHEATING

It has been said that more tools are spoiled by overheating than all other causes combined. The statement is perhaps a bit exaggerated. It is often so easy to detect overheating, and requires some imagination to discover other causes to which overheating is but contributory. Many young enthusiasts, having spotted a coarse fracture, have heated a tool afresh to a more correct temperature and produced after all a waster. It is easy then to lay the blame—and rightly—on the design of the tool or the manner of quenching it. The question, however, is how to prevent the breakage, and no answer, in the form of general rules, can be given save such as have already been discussed on previous pages. The veriest novice, as we have said, can detect flagrant overheating in tools which he himself has not

[1] Taken from Ostwald's *Die Schule der Chemie.*

hardened. And it is safe to affirm that, with few exceptions, all forms of cracking are greatly encouraged by overheating, because it increases the permanent expansion, *i.e.* the induced stress, and at the same time decreases the strength of the material. Especially does it increase the ease with which the apparently insignificant beginning of a crack—such as deep tool marks—can develop and extend.

It is, however, by no means safe to assume that a coarse fracture is necessarily due to incorrect hardening heats; it may be simply an indication that during some preceding operation the material has been burned or soaked at too high a temperature. Experience in dis-

FIG. 72.—Taper overheated and "restored"; effects of overheating still visible.

tinguishing these differences, which can only be described by such lame phrases as "dry" or "staring," is best obtained by careful observation of comparative specimens cut from the same bar of steel. In this manner one may detect differences between material which has been overheated and "restored" and material which has not been overheated that would otherwise escape notice. The piece of steel represented in Fig. 72 was taper heated and quenched; it was then retreated and requenched, but not by any means restored to the same condition as before overheating. The effects of overheating are still visible on the left-hand side.

The sharp corners of such tools as chisels, plane irons, roll turners' knives, etc., are at times overheated on the corners only and not at all in the thicker hardened

parts. This is an indication that the tool has been heated quickly in a furnace much hotter than the correct hardening temperature by an inexperienced or careless person. In its effects this treatment may be worse than out and out overheating, as the lack of uniformity nearly always causes the corners to spring off.

SHEARED ENDS.

Material which has been worked cold, whether hardened or not, is very apt to develop cracks. High tensile rope wire, for example, in the drawn state splits longitudinally with remarkable ease once a small notch has been made on the surface. Small sections of hard steel are frequently sheared into definite lengths for making small punches, drills, etc., but unless the portion of material affected by the shearing strains is machined away, the hardening operation will surely develop an unpleasant percentage of wasters. It also happens occasionally that a shape

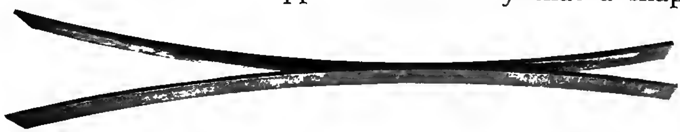


FIG 73.—Longitudinal crack arising from sheared ends.

free from sharp angles and corners has been set out for machining by centre-punch marks. These represent points from which a crack in intensively hardened steel can readily originate, and if they have been almost but not quite machined out, as is frequently the case, it is very difficult, unless fully acquainted with the circumstances, to account at all for the cracks.

Fig. 73, which represents a piece of high-speed steel sheared to length and then hardened, may be quoted as an illustration of cracks arising from sheared ends and edges; and Fig. 74, as showing a crack through the keyway of a metal-slitting saw which has obviously originated from a centre-punch mark. Cracks may originate similarly on the flat face of a machined article, because the rough machining marks are either a distortion of the surface material or act as small notches, or both. These are most likely to be fatal if the machined material has not been made uniformly soft—a frequent occurrence—and then give rise to a complaint backed by that most

obtuse form of statement, viz. that all the articles in question have been made from the same material and treated exactly alike, why, therefore, should some break and others remain sound—which can be dealt with only after frankly ignoring it.

DIFFICULT QUESTIONS. Differences in useful behaviour between articles which are apparently the same, *i. e.* made from the same material by the same process and subjected to the same form of heat-treatment, do undoubtedly occur. And it frequently

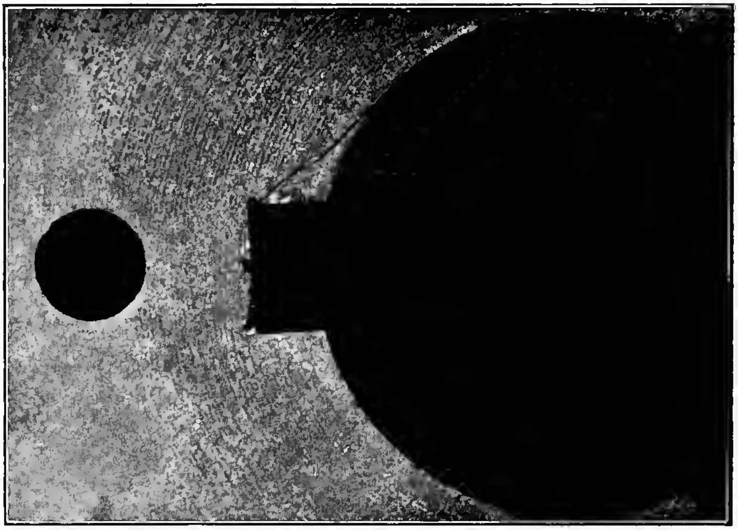


FIG. 74.—Crack originating from centre-punch mark.

happens that an investigation, however exhaustive, of the finished article reveals no cause for the difference. But a difference and a cause for it is unquestionable, and must be insisted upon even if meanwhile a certain amount of ignorance has to be inferred. In many cases the difference arises in the method of working the melting furnace or casting the ingot, of which all traces have disappeared, or rather have been dispersed and attenuated to such a degree that they evade the most minute scrutiny, or though appreciable to difficult and costly methods of research are too slender and indefinite and too remotely

connected with the trouble to carry conviction. If such cases are persistent, one wisely turns back to the base operations and starts afresh; an extended knowledge of works conditions and the sympathetic assistance of workmen are then very helpful, but these are rarely available to those otherwise competent to conduct the inquiry.

Apart from the danger associated with the presence of free cementite, very little attention has been devoted in the previous pages to the composition of tool steel in relation to the occurrence of defects. It has been said that the more nearly a tool steel approximates to a pure iron-carbon alloy the better. This is certainly true so far as very small tools are concerned, and also tools with fine cutting edges formed on a massive core, such as taps, for example. But it is not universally true, for the simple reason that very pure carbon steels harden well only if they are quenched quickly, and therefore as large tools which require to be intensely hardened or for oil-hardening purposes the pure carbon steels leave something to be desired. The remedy, to choose only from amongst those elements occurring in carbon steel, is to increase the amount of manganese and possibly also the amount of silicon. The manganese may be increased up to ·60 or rarely up to one per cent.; it then becomes a question whether Siemens steel of approximately the same composition would not serve the purpose equally well, and the toolmaker, reviewing his experience, finds the question a difficult one to answer.

SIEMENS TOOL STEEL.

A point of comparison between Siemens and crucible steels which is often insisted upon when both are used for tool-making is that the Siemens steel does not withstand so well the re-hardening operation, the reason commonly expressed being that the former does not contain so much "body" and loses its "nature" more easily than the latter. This explanation is a remnant of the time when the manufacture of tool steel was purely an empirical art and the influence exerted by the essentially different composition of Siemens steel had not been clearly realized. These terms, "body" and "nature," have no precise meaning, as we have indicated in

Chap. II; they refer to nothing which can be measured or weighed; they do not belong even to that class of appearances, such as fractures and the shape and position of a crack, which can be appreciated as reliable indications though they cannot be expressed in any scale of units. They belong rather to the primitive jargon of a craft, and may be taken to-day to reflect something of experience, something of prejudice and a semblance of commercial astuteness.

There is greater danger to begin with that a tool made from Siemens steel will break on hardening. This is consequential to the fact that the steel contains more streaks of non-metallic impurity, such as slag and manganese sulphide, and generally is less homogeneous, because it has been cast in larger ingots under conditions of casting somewhat remote from the ideal. But these are incidental disadvantages from which crucible steel is not altogether free.

The main reason why Siemens steels are different, when equally as sound as crucible steel, is that they contain almost invariably larger amounts of manganese than crucible steels, and on this account harden more intensively and to a greater depth, which may be an advantage or otherwise. This obviously increases avoidable stresses if it hardens those parts where hardness is not required, *e. g.* at the roots of teeth, and at the same time lessens the resistance of the material to stress. When Siemens or Bessemer steels are made with small amounts of manganese, those of Swedish origin for example, they are used in many branches of toolmaking with satisfactory results.

If a tool for the reasons stated is more apt to crack at the first hardening, it is still more apt to do so on the second hardening, because on reheating, the stresses, already larger than usual, are in greater danger of being increased to breaking-point. The explanation, however, of this relative behaviour lies not in some mysterious property conferred by a melting process, but in the choice of a material well or ill suited for its purpose on account of its chemical composition.

XII

HARDENING PLANT

THE following conclusions will not be seriously contested by persons acquainted with the facilities generally provided for hardening purposes :—

(1) The equipment of a hardening shop rarely gets the attention it deserves.

(2) It certainly would be difficult in a shop doing general work to provide spick and span appliances for every job that might come along.

(3) Successful artisans in this trade have developed the habit of improvising makeshifts.

(4) Helped by native ingenuity a really first-rate man turns out some astounding pieces of work with a mere handful of regular tools.

(5) So far as the experiment has been tried, the "really first-rate" man does not seem to be spoiled at all when he gets a few specially designed furnaces and loose tools.

For reasons we are already acquainted with, it seems desirable that the heat of a furnace should not be greater than the temperature to which the tool needs to be raised for hardening. It requires otherwise an unusual degree of skill to avoid overheating the corners and thinner parts; and the outer portion must unavoidably be hotter than the interior. Also judgment and ceaseless attention are required in order to determine when the hardening temperature has penetrated throughout.

OPEN FIRES.

The ordinary smith's fire is about the worst conceivable form of furnace for hardening purposes; but it is very handy and inexpensive for occasional jobs, and on this account, though it possessed every objectionable feature possible, it is likely to remain in use and had better be

made the most of. No form of pyrometer can be used in this furnace save such indicators as are mentioned on p. 171. To completely smear the point of a chisel with a fusible paste is the easiest way of observing the irregular manner in which tools are brought up to and beyond the hardening temperature. To obtain anything like uniform heating it is necessary to turn the tool about continually and withdraw it frequently from the fire so that the heat may become approximately uniform owing to the more rapid cooling in the air of the corners which have heated more rapidly in the fire. The open fire can be arranged for temporary purposes and manipulated in various ways to meet to some extent the more exact conditions required for delicate work. The simplest of these ways is to pile damp smithy coal over the hearth and blow the fire till a hollow space has been burned out. From this improvised muffle of glowing fuel very tricky hardening jobs can be done with some precision. Small pieces of coke must be occasionally thrown into the fire, and if it needs brightening up also a few puffs of wind. The arch is kept intact by adding fresh layers of damp coal; it gets gradually larger of course and is then used for larger tools which have been reserved till the last.

If a supply of strongly caking coal is not available, or if only an odd job requires doing, it is easier to build the fire about a piece of wrought-iron or cast-iron piping and harden from the inside of this. The metal is a good conductor, and on that account the heat is more uniformly distributed inside it than it would be under similar circumstances inside an earthenware pipe or muffle; and though the metal piping rapidly burns through it can be replaced for next to nothing from the scrap heap. For handling small taps or drills a blind flange from the gas-fitter, a used shrapnel, or even an old iron saucepan can be packed into the fire and filled with lead or salt in order to secure the advantage of heating a large number of tools simultaneously in a uniform manner.

Where a hearth is used only for the smithing and hardening of tools an arch may be built permanently over it, as suggested by Fig. 75. Once the arch has become

thoroughly hot it radiates back a good deal of heat and helps to keep the temperature uniform. The coke fuel falls through a slit in the top towards the back end, and the whole can be closed up so that the only means of exit for the burnt gases is either of the two front holes, which may be closed if thought desirable with loose bricks. This decreases the tendency to scale. This furnace is also a

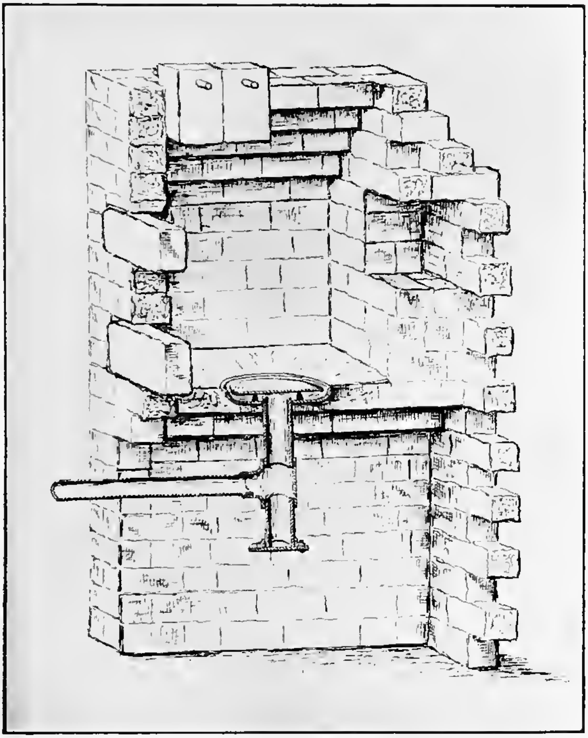


FIG. 75.—Smith's hearth modified for hardening purposes.

convenient one of its kind for hardening high-speed steel as well as ordinary carbon steels.

A great variety of furnaces are in use, fired with solid, liquid, or gaseous fuel, to meet particular requirements. A selection of furnace-makers' catalogues [1] being easily OPEN HEARTHS.

[1] Hardening furnaces are made, amongst others, by Fletcher, Russel & Co., Warrington; Richmond Gas Furnace Co., Warrington; Brayshaw, Manchester; Allday & Onions, Birmingham; Manchester Furnaces, Ltd., Manchester.

obtainable, there is no need to reproduce structural details here. Solid fuel is gradually falling out of use, and can only be recommended either on the ground of economy, or convenience in localities where neither gas nor oil are plentiful and cheap. A reverberatory hearth burning coke mixed with a small quantity of coal is sketched in Fig. 60. The general arrangement is typical of furnaces burning solid fuel which are at present in use for heating different kinds of tools. Relative dimensions vary, of course, and special care must be taken to provide efficient dampers; it is also a convenience to control the draught by means of a door, opening upwards, on the ashpit.

OIL AND GAS. Improved burners have almost entirely done away with the uncertainty formerly associated with oil furnaces, and very crude forms of oil can now be burned without interruption, which brings down the expense sometimes below the cost of coal gas. In point of convenience, however, coal gas (or producer gas) is superior to any other kind of fuel. It can be used with atmospheric burners in any of the usual forms of hardening furnaces to attain temperatures up to 1000° C. For general purposes a tray, which may be of cast iron or boiler-plate steel, is better than a muffle, as the burnt gases surrounding the work in the former case are less harmful on the whole than the oxidizing influences of the undiluted air within the muffle.

Compressed air considerably extends the usefulness of gaseous fuels, and it is sometimes advisable to use it even for lower temperatures in order to drive the heat in any desired direction independent of flues. If the supply is taken from a main or some source not especially provided for the purpose, then some means, which can be readily rigged up and discarded, of varying and limiting the pressure is useful. Fig. 76 is a simple piece of laboratory apparatus and does very well.

The air comes in from the main at A and out to the furnace at B. The pressure is regulated at will by the depth to which the long tube dips below the surface of the mercury. If the required pressure is exceeded, the mercury is pushed back and the excess of air escapes

through E. Some tests made by compressing the gas instead of the air appear to have been very successful. On purely theoretical grounds there should be an advantage in having to control the pressure of gas only, as the pressure of the air at normal temperatures is practically constant.

The chief value of gas or oil-fired furnaces is not that they are clean in use or can be quickly brought to any desired temperature, agreeable as these features are. It

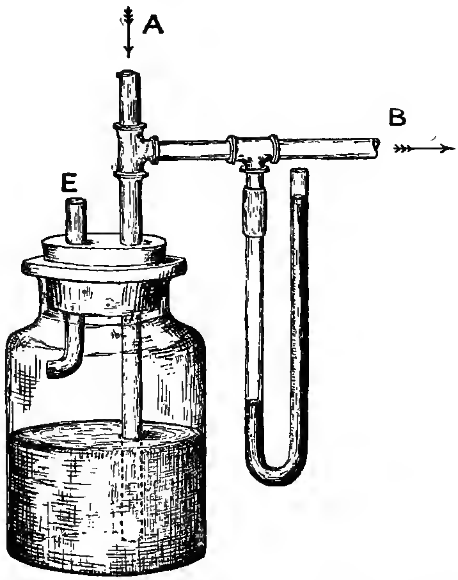


FIG. 76.—Simple arrangement for regulating air pressure.

is rather the possibility of keeping the required temperature uniformly the same for any desired length of time. And so, presuming the gas supply is constant, the furnace may be raised to a suitable temperature and the tools allowed to remain in it until they also reach that temperature. This lightens the responsibility, makes overheating impossible, and with articles of the same kind greatly facilitates the work. It is necessary, however, in the first instance, to look not only to the gas-cock but also to the dampers in order to avoid irregular heating and scaling. The best conditions generally are those which keep the

furnace full of gas flames moving lazily towards the flues. A sharp roaring flame indicates that too much air is being used; but too much gas is also used sometimes, and a pilot flame burning the same mixture of air and gas as the furnace and provided with some means of measuring its temperature is not a useless refinement.

LEAD BATHS.

For many years lead has been utilized in the hardening of files, drills, and edge tools generally; chiefly because it affords, with reasonable care, a uniform heating medium. The specific gravity of lead is very high—higher, in fact, than the specific gravity of steel—and for this reason the article to be heated must be forced into and held down in the bath. The lead has also a tendency to stick in cavities and between teeth, and is easily oxidized, and for other reasons could not be generally used with furnaces of large dimensions. Lead, it is said, can also dissolve its own oxide and sulphide, and through the agency of these substances cause soft spots. One cannot, however, be dogmatic on this point, as such uncertain statements are frequently stretched to explain remote and quite unrelated causes. It must not be presumed that because the heating medium is liquid it is therefore uniform. It is necessary to stir the liquid from time to time, especially if it is heated merely from the bottom over a coke fire or on one side only by being set in a flue.

SALT BATHS.

By merely substituting salt for lead in the old form of pot, we handicap the salt bath to a serious extent. All salt mixtures suitable for steel-hardening purposes melt at temperatures considerably beyond the melting-point of lead, and, as salt mixtures are much worse conductors of heat, it is difficult to avoid the incrustation of frozen salts about the top of the pots. From this cause, no doubt, arose the practice of adding substances such as nitre, soda ash, and caustic soda to the salt mixture in order to reduce its melting-point, and for this reason many undesirable features have become associated with the salt bath, which can easily be avoided in a properly designed furnace.

Considerable impetus has been given to the use of salt baths in this country by Mr. Brayshaw, of Manchester;

a view of his furnace is given in Fig. 77. There is probably no furnace extant better suited for exact work of an ideal kind, though opinion is somewhat divided over its merits as a workshop tool; the writer, however, has had

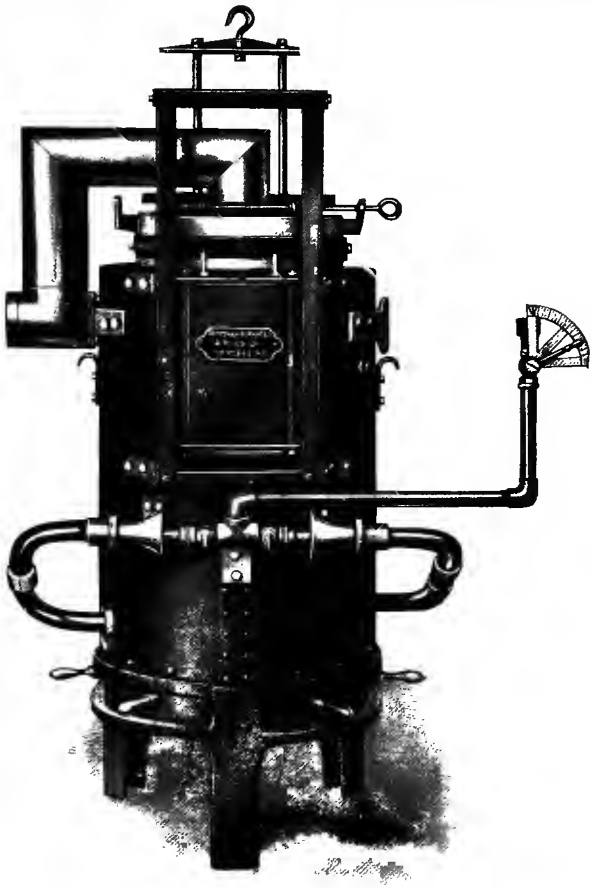


FIG. 77.—Brayshaw's salt-bath furnace.

no personal experience with it, and can therefore make no comment.

A simpler form of furnace is illustrated in Fig. 78. The furnace body consists of a wrought-iron cylinder with brick lining. There is an intermediate air space to reduce radiation, and for the same reason a sheet of asbestos is sometimes laid on to the outer surface of the

wrought iron. A single burner of the annular type rests on the bottom of the furnace body, and the pot containing the salt mixture is supported by lugs, or a perforated rim, which rests on the brick lining. The flame and hot gases, in passing between the outer surface of the pot and the inner surface of the brick lining, give up much of their heat to numerous studs projecting from all parts of the surface of the pot, and are eventually diverted on to the

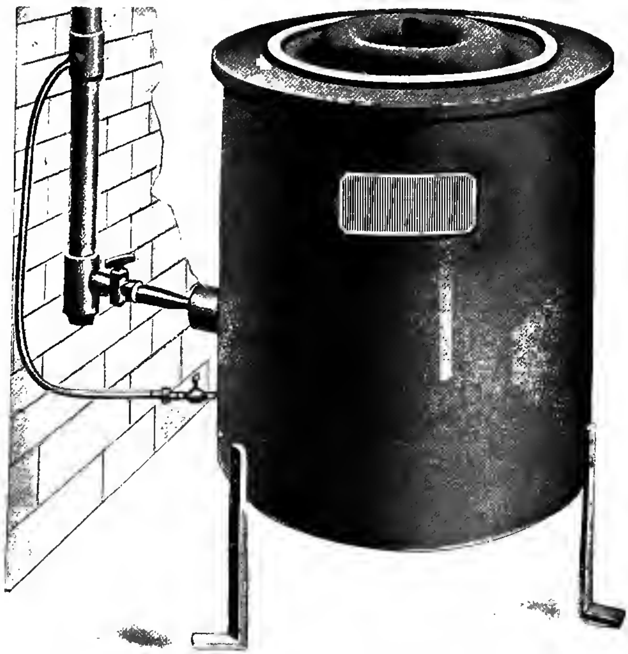


FIG. 78.—Very simple form of salt-bath furnace.

surface of the molten salt by means of the curved cover. In this way the pot is evenly heated to the extreme upper edge, and an accumulation of frozen salt becomes impossible. At the same time the products of combustion impinging on the surface of the salt, or lead as the case may be, minimizes the amount of atmospheric surface oxidization.

PROPERTIES OF MOLTEN SALTS. On immersing a tool in the molten salt bath, the temperature of the salt in its immediate neighbourhood is reduced below the melting-point, which causes a layer of

salt to freeze around the tool. This salt layer is a comparatively poor conductor of heat, and remains almost intact until the tool has gradually absorbed sufficient heat to raise it to the melting-point of the salt. In no case can this occur below low redness, and after that a more or less rapid heating is unavoidable. On withdrawing the heated tool, the molten salt adheres and completely envelops it. On this account the temperature of the tool falls more slowly and regularly. The salt sheath, however, does not interfere with the quenching, but dissolves as soon as it comes in contact with the water, and leaves a clean metallic surface barely oxidized or even tarnished.

A further advantage, which is not so well known and is insufficiently utilized, is the ease with which the melting-point of the salt-bath mixtures may be varied. Assuming that we have to deal with a steel which must be heated to at least 750° C. in order to harden it at all, we may, by way of example, choose a salt mixture for the bath which melts at 760° C. The minimum hardening temperature must obviously be maintained in order to keep the bath molten, and the steel object being handled must also reach nearly the same minimum temperature before the salt, which on immersion immediately congeals around it, can melt off. A temperature of 20° C. or even 30° C. beyond this minimum, unless unduly prolonged, can do the tool no harm, and it is an easy matter for an inexperienced workman, without the aid of any form of pyrometer, to keep within this margin. On withdrawing the tool from the furnace, after the congealed salt has melted clean away, the liquid salt drips off, but very shortly a coating of it crystallizes on the surface, and indicates that the quenching should be proceeded with.

ADVANTAGES OF SALT BATH.

This mode of hardening is certainly a great improvement in point of accuracy on the usual shop practice, and is quite independent of the workman, the state of the weather, or other possible contingencies. But it is rather slow, and does not reach the best attainable hardening conditions required for faultless work on complicated

shapes of varying section. The thinner sections and corners of such tools will always heat more rapidly in any furnace—though the difference is less marked in the salt bath than in other forms—than the more massive parts, and as uniform heating is essential to success, it is necessary to insist on the temperature of the furnace itself being correctly regulated, so that objects being hardened may be left exposed to the heat as long as is necessary for all parts to become evenly heated throughout, without any of the parts becoming overheated. That is to say if the temperature of the furnace is uniform and suitable, the temperature of the object may, generally speaking, be left to take care of itself.

Ideal conditions. From these considerations and the indications of the thermal curve already mentioned (Fig. 47), we may arrive at what are believed to be the ideal conditions of steel hardening as far as they can be stated in general terms. That is to say, the objects should be heated some twenty or thirty degrees beyond the thermal change-point on the heating curve, and be allowed before quenching to fall to a uniform temperature some ten degrees above the cooling change-point.

These stipulations cannot very well be carried out with one salt-bath furnace, because the intermediate cooling in the atmosphere through a large range of temperature, say from 780° to 710° C., is not quite uniform, in spite of the protective salt coating. The operation is more precisely carried out as follows, but still, be it noted, without necessarily making direct use of any form of pyrometer—

In the first place, the object is heated some 30° C. beyond its minimum hardening temperature in the salt bath as already described or in any other form of furnace. It is then transferred to a second bath, whose melting-point is say 710° C., and whose temperature is easily maintained at quite negligible cost several degrees beyond this by the heated objects constantly being added. In this second bath the object cools uniformly to the prevailing temperature, and on withdrawal is enveloped in a coating of fluid salt, which, after a moment's delay,

crystallizes over the entire surface, and indicates that the quenching should be made.

Thus are the stipulations of the modern theory and practice of hardening satisfied. The seeming complication has no real existence. The method is admirably adapted to the quick despatch of regular work, whether of a repeat or varied kind, and the refinements can be easily dropped or taken up according to circumstances. Moreover, a couple of furnaces having circular baths eight inches diameter by ten inches deep can be accommodated in twenty square feet of floor space, and be installed for from twenty-five to thirty pounds.

SOFT RINGS.

It is occasionally necessary to harden one end, side, or surface of an article without hardening the rest, or to preserve the centre, or a strip round the middle of an object, in the unhardened state. Even where special appliances are available the risk of dangerous tension between the hardened and the unhardened parts is often very great. With a couple of furnaces some difficult operations of this kind are fairly easy. The object is heated in the first bath as usual, and on withdrawing is cooled on the parts which are to remain soft by the application of pads of wet asbestos, etc., until the temperature of these parts has fallen below 680° C. say, to a scarcely visible redness. In the meantime the remaining uncooled parts will not have fallen by any means so low as 700° C., and after immersing in the second bath the temperature becomes equalized. But on withdrawing from the second bath and quenching, although the temperature is uniform throughout, only those parts of the object which were not cooled below 680° C. will become hard, and between the hardened and unhardened portions the greatest attainable graduation of tension will exist.

SPIKE INDICATORS.

We have already referred to the ease with which the melting-point of the salt-bath mixture can be varied at will within certain limits and used to control its temperature without the use, if need be, of a pyrometer. It should also be said that the melting-points of some mixtures remain practically constant over long periods, in spite of the small amounts of oxide of iron which accumulate

and float about in the bath. This feature enables a very inexpensive but fairly accurate form of temperature indicator to be used which is called the "spike."

The "spike" is nothing more than a round piece of wrought iron which tapers from one end to the other. On immersing such an object into a bath, the quantity of salt which congeals around it will obviously depend on the number of degrees the temperature of the bath is over and above its melting-point. It is equally obvious

FIG. 79.—Examples of "spike" before and after use.

that the rate at which the congealed salt dissolves off again will depend on the same circumstance. If, therefore, the "spike," when immersed, is always at a constant temperature, say 100° C., and allowed always to remain in the bath for say one minute, then the weight of the salt still adhering, or otherwise the length of the spike from which the salt has clearly melted, will be a measure of the temperature. See Fig. 79.

The "spike" is calibrated once for all by comparison with a standard thermo-couple, and may then be duplicated to any desired extent. Previous to immersion it is kept at a constant temperature of 100° C. in a piece of

apparatus made from an ordinary lever-lid tin as shown in Fig. 80.

The melting-points of salt mixtures suitable for use in hardening ordinary carbon steels vary between about 600° and 800° C., and for tempering the same from about 200° to 350° C. At temperatures much above their melting-points the former vaporize to a slight extent and cause iron objects in their neighbourhood to rust quickly. Small particles of iron in the form of magnetic oxide accumulate in the bath and may adhere to very fine-toothed articles such as files, and cause the tips of the teeth here and there to remain soft after quenching. If the files are dipped into a solution of ferrocyanide and allowed to dry before putting into the bath, this does not occur. The remedy, however, is not quite satisfactory, as each coating of ferrocyanide decomposes and adds more iron oxide to the bath. Potassium cyanide would be free from this objection, but it is so poisonous a substance that its regular use cannot be recommended. Experiments made with other substances of a harmless kind have not been at the same time successful and commendable, and one is obliged reluctantly to conclude that, so far as files are concerned, the lead bath is preferable. DISADVANTAGES OF SALT BATHS.

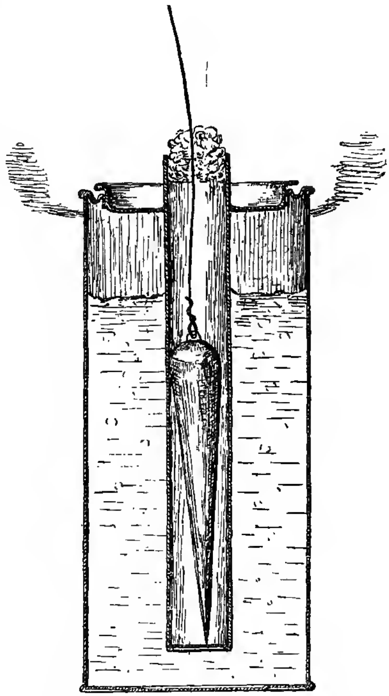


FIG. 80.—Arrangement for keeping the "spike" at 100° C.

A plain rectangular cast-iron trough, an old tub, or even a bucket may in some circumstances be everything that is required for holding the hardening fluid. For QUENCHING TANK.

varied work, however, a tank which can be readily adapted to special purposes is a great convenience. A good supply of water should be led into it from the bottom and branch into at least two arms, as in Fig. 81.

These branches are screwed at the ends so that any desired fittings, such as those already mentioned in Chapter X, may be easily and firmly attached. The waste pipe at the top of the tank may empty around

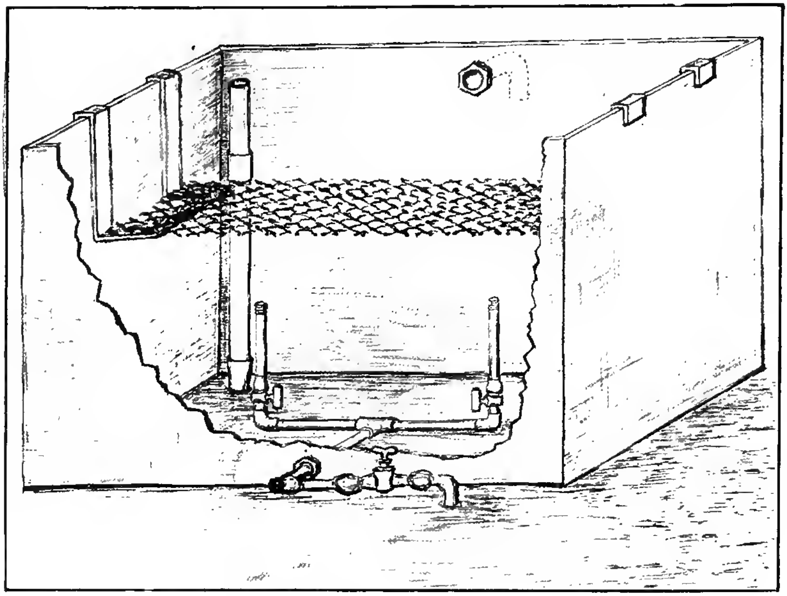


FIG. 81.—Universal hardening tank.

an adjacent oil tank for cooling purposes, or directly into the drain. The upright pipe in the left-hand corner fits into a taper hole in the bottom of the tank which serves to empty the tank entirely. The upper part of this pipe should be wider than the lower half, and screw over it to any extent in order that the water in the tank may be arranged and maintained at any desired level. The perforated grid which hangs from the sides is intended, in conjunction with the adjustable overflow pipe just mentioned, to facilitate the quenching of objects which are hardened over a definite part of their length only.

The fittings suggested by Figs. 63 and 64, and others already referred to, indicate to some extent to what varied uses a universal tank can be put; but the main advantage lies in its adaptability to any unusual job which may be presented.

Although we have intimated that the waste water may be used for cooling an oil tank, it is really a very inefficient way of cooling oil to pass water about the containing vessel, because the oil itself is a poor conductor of heat. A readier way of cooling a small quantity of oil is to blow air through it; or, if the quantity is large, to pump it through a nest of small water-cooled pipes.

LOOSE TOOLS.

The equipment of a hardening shop includes also an assortment of loose tools which need not be separately described; tongs of varied lengths and strengths with curved and straight jaws, so that an object may be readily and suitably handled; rods of iron for making into hooks; and sheet-iron and asbestos for protecting the parts which require heating very slowly or not up to the hardening temperature; iron piping, case-hardening boxes, or any receptacle which can be closed, and a supply of iron and steel filings so that an article may be packed for close annealing; and scores of other things which can frequently be picked up from the scrap heap and cost nothing, but are worth a great deal when a chance-job has to be done quickly and well.

A pair of tongs with long jaws is very convenient for holding a quantity of drills, bits, etc., which require to be heated in molten lead at one time. If the articles are of uneven thickness and one jaw of the tongs be made hollow and one flat, a piece of soft wood may be put in the hollow jaw so as to grip all the drills. Magnets of special shapes have also been devised for holding simultaneously a number of small tools whilst they are being heated in salt baths and quenched.

XIII

PYROMETERS

GENERAL CONSIDERATIONS.

THE metallurgical millennium promised to all who would install pyrometers in their furnaces is still a long way ahead. Respecting the importance of pyrometric control of furnaces used for annealing and hardening there can be no question; but obviously the difficulties of quenching, etc., remain as great as ever. Having obtained pyrometers to register and control furnace temperatures, it has, in many instances, been found necessary to obtain some one to look after the pyrometers. The experienced workman who judged by the eye, now and again, either for particular or diverse reasons, made mistakes, but also the pyrometer may do so; and whereas the workman generally righted himself in time to within his usual limits of error, the instrument generally goes from bad to worse.

It is not necessary to enumerate the diverse reasons for which a pyrometer may give incorrect readings. It is, however, important to note that the defect may appear suddenly or increase gradually, and in either case without being suspected; particularly if the instrument is regarded (wrongly) as a substitute for the human eye and judgment, and these latter, being no longer trusted and responsible, are no longer trained and consciously used to determine temperatures. In any case it is necessary that the instruments should be regularly proved and standardized.

LARGE FURNACES.

An oft-quoted rule, which is supported alike by considerations of economy and experience, is this : "Use the lowest temperature which enables the desired result to be obtained." And an effort often made after installing a pyrometer is to arrange the temperature as near the

margin as possible. The "irreducible minimum" in temperature is a two-edged sword for the average operator who decides to surrender his judgment to the indications of a pyrometric indicator; the step usually leads to considerable trouble, but also to much instruction. The danger lies, to some extent, in the fact that industrial furnaces have never the same uniform temperature throughout their length and breadth, or from bed to roof. Something less than the temperature registered by the pyrometer, which is that of its immediate neighbourhood only, is attained in other parts of the furnace, and consequently some of the objects being heated, or parts of them, may not respond to the treatment. The pyrometer, of course, is not responsible for the disappointment, as it has never been claimed that the instrument will overcome faults in furnace design, although it is much to its credit to have shown so clearly how badly reheating furnaces are frequently constructed.

The idea of an "irreducible minimum" in temperature must be compromised with, and it is advisable, if the instrument has not been firmly fixed, to take readings of different parts of the furnace and plot out a temperature chart. If this is done for different modes of firing or charging the furnace, the trouble involved is well repaid by the information gained. The variations disclosed by such a survey are usually surprising, but as uniformity of temperature in any object being treated is generally of much greater importance than very exact readings on a temperature indicator, it will be conceded that there is scope between the neighbourhood of the pyrometer tube and the four walls of the furnace for human judgment and the best rule-of-thumb practice, as well as other qualities which cannot be hitched on to a wire or regulated by clockwork.

RULE OF THUMB AND SCIENCE.

The influence of pyrometers on the design of industrial furnaces has already been considerable. But engineers are rarely expert furnacemen, and the important finishing touches and minor alterations which make a furnace work reliably and uniformly are frequently made by ingenious workmen in ways difficult to describe. It is

nearly always a mistake to install a pyrometer in opposition to a man; to fasten it into the furnace and enforce its indications willy-nilly is the least profitable use to make of it. A very moderate workman is a long way ahead of the best instrument used in that manner. The freer the instrument is to be used now in one part of the furnace and then in another, as the judgment of the workman demands, the more interest he takes in it, the less he feels his skill to be superseded by it, and the more perfectly the desired object of heat treatment can be attained. The control which an intelligent man with such assistance obtains and can exercise over his furnace is quite remarkable and gratifying.

One hears too frequently from people who, through neglect, are disappointed in the original and obvious use of a costly temperature-recording instrument, that it nevertheless is worth the money as a check and tell-tale to announce, without fear of intimidation, when the firer has been asleep or for other reasons neglected his duty. Such instruments are not worth consideration as pyrometers, and it may be suggested that people do not fall asleep over work they are interested in. A firer who was fit for his duties, given a suitable instrument, might keep himself awake and go very far towards removing the vexatious variations of temperature which father innumerable evils and against which a fixed indicator is of little value. This way promises better than any other way to improve the design and bring the temperature of large furnaces under ready control.

OPTICAL PYROMETERS.

The man who tells temperature "by the eye" uses a kind of optical pyrometer, *i. e.* the sensation of a colour which changes as the temperature rises. This primitive kind of instrument is wonderfully sensitive, but not thoroughly reliable. It is subject to physiological derangement; it also does not enable the observer to state temperatures in precise terms, and therefore does not provide accurate information for general use. The sensation of colour is comparative, and depends entirely, so far as brightness of colour is concerned, on the condition of the surrounding objects. Changes in the sky,

in the artificial lighting of the shop, or the flame emitted by the furnace itself even, need to be taken into account. In order to help out the insufficiency of the eye, red glasses of different tints are occasionally used, which, on being illuminated from the back by some unvarying source of light, enabled them to be looked to as standards. Varied suggestions akin to the above have been proposed over and over again, but appear to be only rarely used.

A really serviceable instrument based on a comparison **Wanner.**

Fig. 82.—The Wanner pyrometer.[1]

of colours, one of which can be varied at will according [illegible] until it corresponds in brightness [illegible] observation, is known as the [illegible] pyrometer, and is made by The Paul Schmidt and Desgraz Co., Ltd., of London. See Fig. 82.

When first introduced it could not be used for temperatures below 900° C., but it worked very well at higher temperatures. It is generally considered to be better than

[1] It seems needless to describe the construction of any of these instruments, as such information is always available in trade circulars and is constantly appearing in technical journals.

any other instrument for taking the temperature of molten metals or metal-melting furnaces, though a really satisfactory apparatus for this purpose, so far as steel and some other high melting-point metals are concerned, has not yet been devised. The Wanner outfit is now made for temperatures down to 600° C. A similar instrument registering temperatures from 700° C. upwards is made by the Cambridge Scientific Instrument Co.

FÉRY. Two forms of the Féry pyrometer are in use. The

FIG. 83.—Sighting the Féry radiation pyrometer.

older form consists of a tube containing a delicate thermo-couple exactly in the focus of a silvered concave mirror which reflects the heat rays of the furnace on to it. The temperature of the couple is then indicated on a sensitive [illegible] olt-metre. The newer form does not vary much in [illegible] rance from the older, but the thermo-couple at the [illegible] of the mirror is replaced by a coil of two dissimilar metals which unwinds more or less according to its temperature. The coil is very small and fastened at one end; the other end is attached to a small aluminium

pointer which moves over a graduated dial. These instruments require to be accurately focused and carefully handled.[1]

They are claimed to be universally applicable, but appear to be better adapted for giving indications and making records of temperatures of furnaces which are operated without interference for long periods—such as annealing furnaces, case-hardening ovens, and automatic hardening machines. The first form, at least, does not give anything like an accurate indication of the temperature of molten steel as it runs from the furnace.

RESISTANCE PYROMETERS.

The essential part of resistance pyrometers is a fine platinum wire, wound on a mica frame, whose resistance to the passage of a small current increases at a rate nearly proportional to the temperature. As electrical resistances can be very easily measured, this form of pyrometer is more sensitive than any other. It is especially well suited for use in positions where it can remain for long periods undisturbed, such as in hot-blast mains, furnace flues, salt-bath furnaces, etc. It is also especially valuable where changes occurring over a short range of temperature need to be carefully observed, as the instrument can be adjusted to almost any degree of delicacy. It is, however, expensive, it is limited to temperatures well below 1200° C., and the cost of replacing the porcelain sheaths which protect the couple may be a serious item unless it is cautiously handled. It is also not easily repaired except by a skilled man, which involves the unavoidable delay and annoyance of returning it to the maker.

THERMO-COUPLES.

The "couple" temperature reading outfit is more widely used than any other, and therefore requires fuller consideration. It consists in principle of two wires of dissimilar metals fused together and in that form known as a couple. When the junction is heated an electric current is generated whose electromotive-force varies with the temperature and is measured by means of a millivolt-meter. For tempering baths or work which

[1] A fixed focus optical pyrometer is made by the Foster Instrument Co., Letchworth, Herts.

does not involve temperatures beyond 650° C., a couple consisting of one wire of silver, or copper, and the other of constantan [1] can be used; such couples are very cheap, and can be easily replaced. For moderate temperatures, say up to 900° C., couples made from the more refractory baser metals may be used; they too are cheap and give widely spaced readings on strongly built indicating instruments. But for all ranges, including high-temperature work, only two kinds of couples are in general use. In both, one wire consists of platinum; the second wire in one case is made from an alloy of platinum and iridium, and in the other from an alloy of platinum and rhodium. The two kinds of couples are then spoken of as platinum-iridium and platinum-rhodium couples. The former generates the greater electromotive-force for any given difference in temperature, and therefore the scale on the indicating instrument is a more open one; it is also somewhat cheaper. But these advantages are more than counterbalanced by the fact that iridium couples are more apt to become brittle and are considerably damaged at temperatures of 1000° C. and over. To avoid being misled by these changes it is necessary to restandardize the couples rather frequently. The changes in E.M.F., according to Stupakoff [2] and others, occur at about 1800° F. (983° C.), and are due to partial volatilization of the iridium which occurs at this temperature. Platinum-rhodium couples can be safely used at much higher temperatures, preserve a constant E.M.F. for longer periods, and are less brittle after extensive use. No kind of couple should be needlessly exposed to high temperatures.

Protecting tubes. Either kind of couple can be easily damaged by careless use. The unprotected wire should not be exposed to the action of reducing gases; a stream of unburnt coal gas impinging on the naked wires will make them exceedingly brittle in a few hours. Contact with oxides of iron and some silicates is also very objectionable, and they must, of course, be rigorously protected, like all platinum goods, from contact with metals or metallic

[1] An alloy of copper and nickel of high E.M.F.
[2] *Iron and Coal Trades Review*, November 26, 1909, p. 853.

fumes with which they readily alloy. The two wires are insulated by passing them through parallel holes in short lengths of clay or porcelain rods. The bottom rod is countersunk on the end so as to protect the actual junction, and the whole is attached to a head which may be made up as indicated in Fig. 84 from a vulcanized fibre or ebonite disc, carrying two brass terminals, and a piece of gasfitters' ordinary wrought-iron stock. The resistance of the couple, which varies with its length, and may vary in the same couple with use, is adjusted by means of a small coil of manganin resistance wire wound on the small bobbins attached to the underside of the fibre head.

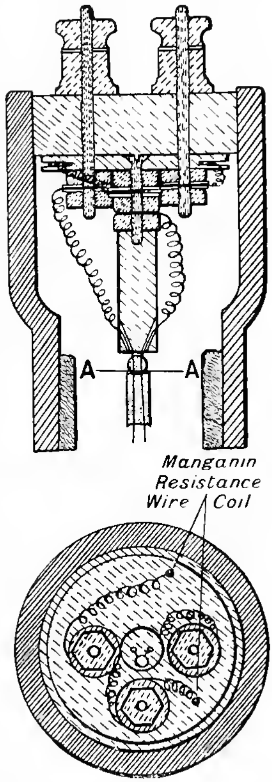


Fig. 84.—Sectional plan and elevation of couple head.

The protecting tubes for platinum metal couples used formerly to be made of porcelain, which was fragile in itself and sensitive to sudden changes of temperature; it was therefore costly. To use an iron sheath only is risky, as iron, and particularly wrought-iron, is not impervious to hot gases, and furnace gas soon makes platinum wire brittle. The use of an iron sheath over an inner tube of porcelain or fused silica appears to be an ideal protection for platinum couples, but the protected couple bears a certain resemblance to a poker and is sometimes spoken of and used as such. In any case the iron tube may sag, and in doing so, or during the subsequent effort to straighten it, the inner tube gets broken without any responsible person being the wiser.

Having had experience with most of the forms of thermo-couples and methods of protecting the expensive

wires, the author recommends the use of a single tube made from thick-walled silica tubing. Such a protecting tube is certainly fragile, it looks fragile and everybody knows it; it therefore gets treated accordingly. But if the diameter of the tube is, say, one to one and a quarter inches, its average life when in daily use in a hardening furnace, accidents excepted, will not be far short of six months; and when once it gets broken there is no overlooking the fact, and no danger, therefore, of the expensive couple wire itself being exposed to the deteriorating influence of furnace gases. Paradoxical as it may seem, the cost of maintaining over one hundred platinum metal couples decreased by nearly one-half after the protection (!) of an outer iron sheath was discarded, the couples in question varying in length from three to twelve feet, and the range of temperature measured being generally up to 1000 C., and in a few cases up to 1200° C.

RECORDERS.

With many forms of apparatus now available the temperature may be read off as required, and also at the same time be automatically and continuously recorded. Those recorders depending on the photographic development of an image traced by a spot of light reflected from a mirror galvanometer are less convenient than those whose records are visible any time after they are made. These latter are traced on a drum or on a sheet of paper moving horizontally by an arrangement which depresses the needle of a millivolt-meter each minute or oftener. They can also be used for recording simultaneously the temperature of several furnaces with the aid of a self-acting switch which connects the terminals of each couple in turn with the recorder. Of the various forms of instruments now being sold, Fig. 85 represents only one of many reliable types. Thermal curves which clearly show the critical change-points on heating and cooling can be traced with next to no trouble, and without any regard to the shape of the specimen, on a good recorder.

There are many reasons why at least one automatic temperature recorder should be installed in every works seriously using heat-treatment processes. If that one is

wisely used others are likely to be added to it. With this probability in mind, the author would recommend that the indicator intended for the use of the furnaceman should be of the suspended coil type with an internal resistance of the same order as that of the recorder—say 450 ohms. If it is intended to carry the indicator from place to place, then a pivoted coil instrument is preferable, but not otherwise. The couples can be made,

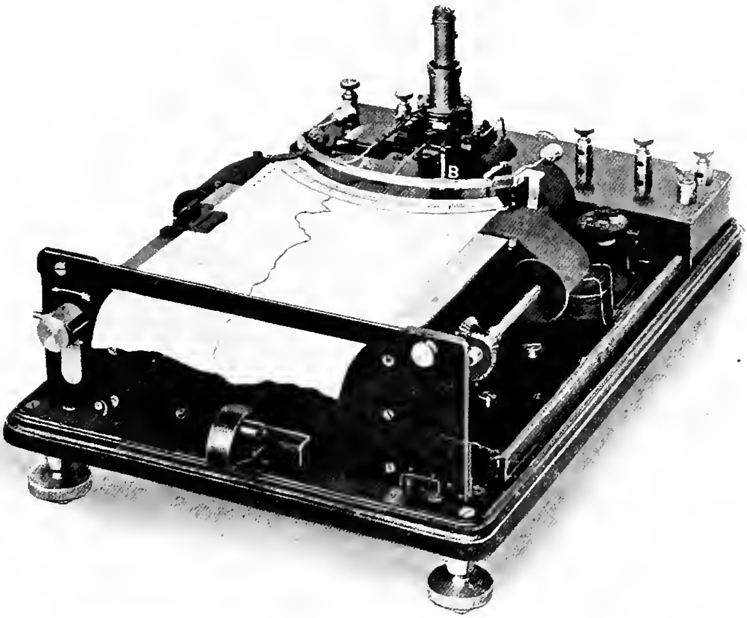


Fig. 85.—Siemens recorder with cover removed.

repaired, and calibrated on the spot, and this is highly desirable when half-a-dozen couples or less are in use, though a capable man would be able to repair and keep fifty of them in order. In this work a recorder would be found useful.

Also by means of an automatic temperature recorder a determination of the critical thermal ranges of various steels can be made with surprising ease; in fact, a couple in imperfect contact with a large mass of work in the furnace will frequently indicate the critical change-point on the record as the furnace is being heated. But if a THERMAL CURVES.

heating and cooling curve is being made intentionally, the specimen under observation should have a hole bored to the centre of it in which the couple can be inserted. The specimen may weigh as much as twenty or thirty pounds and be heated in an ordinary gas-fired furnace, using a tray instead of a muffle, in which case a hole one half-inch in diameter will receive the couple protected by a thin sheath of fused silica; or it may weigh not more than one ounce and be conveniently

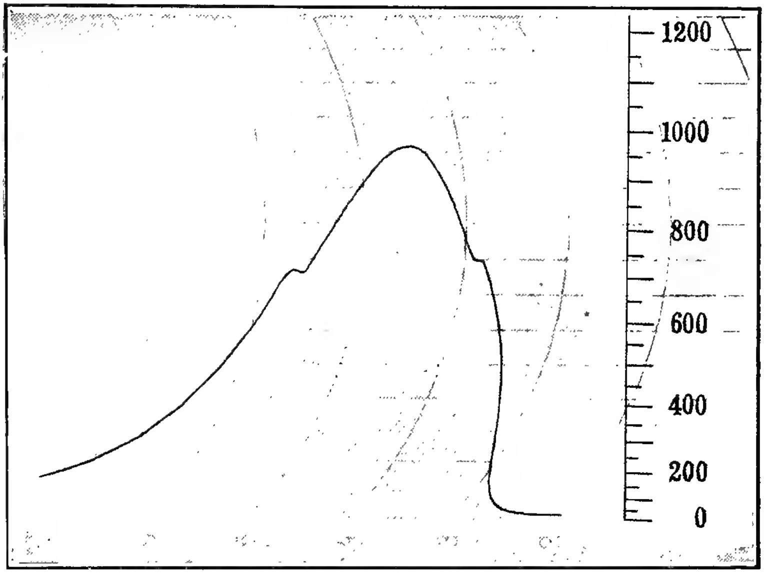


FIG. 86.—Thermal curve of tool steel drawn automatically by recorder.

heated in a small vertical electric furnace, or even over a blast lamp suitably aided by a non-conducting mantle, in which case the insulated but otherwise naked couple is inserted into a small hole about three millimetres in diameter. The kind of curve produced by either of these means is illustrated in Fig. 86.

COLD JUNCTIONS.

The end of the couple inserted in the furnace is spoken of as the hot junction (H.J.), and the other end connected to the brass terminals in the head as the cold junction (C.J.). The current registered on the indicator depends on the difference in temperature between these two ends.

But the reading on the indicator would not be the same, *e. g.* under the following circumstances—

H.J. 700° C. – C.J. 0° C. difference 700° C.
H.J. 750° C. – C.J. 50° C. difference 700° C.

although the difference in temperature between the two ends is the same in either case. The irregularity is due to the fact that the E.M.F. generated is not strictly proportional to the temperature, and cannot, therefore, be represented by a straight line. In order to avoid any error creeping in through this cause, it is advisable to standardize the instrument in the first instance under practical conditions, that is to say, with a C.J. of 25° C. If in actual use the C.J. deviates appreciably from 25° C., then the difference after multiplying by 0·75 should be added or subtracted accordingly. The result will be correct to within two or three degrees over a range of variation in cold-junction temperatures between 20 and 90° C.

The variation in cold-junction temperatures may be considerable as between different parts of the year, and even different parts of the day, in workshops where rows of furnaces are in use; and it was formerly necessary to affix a small thermometer in the couple head so that the correction just referred to could be made. But it is now possible to purchase leads which at low temperatures possess the same thermal constants as the couple wire; the cold junction is therefore virtually transferred to the position occupied by the temperature indicator or recorder and ill effects of variations do not exist.

REPAIRING THERMO-COUPLES

As all forms of thermo-couples are subject to varying degrees of deterioration or may get accidentally broken, it is a great safeguard and convenience to be able to do simple repairs and calibrations on the spot. Defects in recorders and indicators rarely arise, and can be dealt with only by an experienced instrument-maker.

The re-fusion of a broken couple is frequently necessary, but can be carried out in a few minutes. A stream of compressed oxygen is allowed to pass through a small blowpipe—such as is used for blowpipe analysis by pro-

spectors—into the flame of an ordinary spirit lamp. The deflected portion of the flame is very hot, and suffices to melt the two ends of the broken couple which are brought together within its range. Made in this way, the fused junction after a little practice consists of a small sphere of metal the size of a pin's head with the wires running smoothly away from opposite sides of it. The two wires may also be twisted together over a length of two or three millimetres and the extreme end fused as before; this method required less skill, but does not make so neat a finish about the junction.

CALIBRATION. The laboratory method of calibrating is to insert the couple into molten substances which have a definite freezing-point, and during cooling to observe the position on the scale at which the temperature remains constant owing to the evolution of the latent heat of fusion. This is also the most suitable method for industrial purposes, presuming that correct substances, having definite freezing-points, are chosen. The substances chosen should have the following properties—

(1) The freezing-point should be sharp and continuous for at least as long as is necessary to comfortably make an observation.

(2) It should not be subject to oxidization, and its freezing-point should not be altered if it should chance to become oxidized.

(3) Its indication should be the same, however often the observation may be made.

(4) It should not attack the iron casing of the couple, nor should it be injuriously affected by contact with the iron casing at high temperatures.

In short, what one requires is a substance that can be melted in an iron or a graphite pot in a smith's hearth without any of those special precautions which, though easily complied with in the laboratory, it is almost impossible to observe in the factory.

Tin, lead, and zinc can be used, and are easily obtainable in a sufficiently pure state, but they oxidize very readily, and, moreover, their freezing-points—232° C., 327° C., and 419° C. respectively—are too low for general

use. The freezing-points of antimony (632° C.) and of aluminium (657° C.) come nearer working temperatures, but these metals are not easily obtained of a sufficient degree of purity, and they also readily oxidize and are otherwise easily contaminated. Silver, which freezes at 962° C., is excellently suited for the purpose, but it is expensive. Copper may be used, but its freezing-point, 1084° C., is subject to a variation in temperature of 10° C. by exposure in the molten state to the atmosphere.

While, therefore, metallic substances can be satisfactorily used under suitable conditions, they are by no means as convenient as could be desired, nor do the freezing-points of those which might be used fall within the temperature range mostly used in the heat treatment of steel and iron. On the other hand, however, some salts of the metals meet almost every requirement, and from among the great number of mixtures which can be prepared a suitable substance may be selected for making a calibration in any desired range of temperature.

Take, for example, ordinary table salt; not any of the fancy salts or the non-caking varieties, which contain something else besides salt, but the common loaf brand. Its freezing-point lies always between 795° and 800° C., and the same material can be used over and over again with perfect satisfaction. The manner of using it is as follows: Fill an iron or a plumbago crucible which will hold about a pint with the crushed salt and set it on a smith's hearth, or heat it by any other available means until the salt becomes quite molten. Then place the warmed end of the couple into the molten salt, and close to the other end (the cold junction) tie a thermometer. When the hot junction has had time to attain the temperature of the molten salt, remove the crucible from the fire, or turn off the gas, and pack it amongst dry warm coke. Now carefully observe the indicator, which begins gradually to fall. As soon, however, as the salt begins to freeze, the indicator remains stationary or it may even rise slightly, and it does not again begin to fall until the salt is quite set. Observe also the tempera-

ture of the cold junction as indicated by the thermometer and calculate as follows—

Instrument, originally calibrated at say ..	25° C.
Pointer came to rest against mark	790° C.
Cold junction temperature	30° C.

Therefore, 790° C. on the indicator corresponds to $790 + (30 - 25) \times \cdot 75 = 794°$ C., that is, the instrument is indicating six degrees low.

The salt may be remelted in a few minutes in order to repeat the observation; and finally the crucible, when cold, may be wrapped in paper and kept available at a minute's notice to check any instrument which may be in use.

It may be, and usually is, desirable to have several substances whose freezing-points lie along the range of temperature over which the pyrometer is being used. Such substances, in the form of salt mixtures having guaranteed freezing-points, are manufactured by the Amalgams Company, Ltd., of Sheffield.

In using either salt mixtures or any other substances for calibration purposes it is absolutely imperative that all traces of one substance be removed from the couple before it is immersed in another substance. If salts are used it is sometimes much easier to slip off the iron tube and immerse the naked couple in the molten mass. The salts do not harm the couple in the least, but the same method cannot, of course, be used with metallic substances.

When the naked couple is available, a piece of, say, 0·9 per cent. carbon tool steel, whose critical temperature on heating has been determined, may be used over and over again, if a hole is bored into it to receive the end of the couple. The piece of steel containing the couple should be placed in a small clay crucible, and may be heated either on the smith's hearth or over a brazier's lamp, but always under the same conditions. A piece of steel prepared in the manner indicated has an advantage over most other substances which might be used for calibrating pyrometers. It can easily be obtained

in any desired quantity, and it can be replaced without trouble. It is true that only a very limited range of temperatures can be checked in this manner, but the range for most purposes of heat treatment is the only one that is of any importance.

As this simple method of checking the indications of a couple has been discredited, the following results are of interest: An observation was made with an ordinary naked couple and portable indicator by four persons at different times. The readings at which the halt on heating occurred were reported as 739° C., 742° C., 741° C., and 743° C. respectively. With an arrangement especially designed for making thermal curves the halt occurred at 740° C.

The calibration of industrial pyrometers, whether carried out in the works or by the instrument maker, may be accomplished, as we have seen, by means of substances whose melting-points, or rather freezing-points, are fixed and easily observed. It is obvious, therefore, that the temperature of a furnace which could liquefy one of these substances would be higher than its known melting-point; and that of two substances, if one were melted and the other not, then the temperature of the furnace under observation would lie somewhere between the two. The Seger cones which for many years have been used in pottery kilns are well-known examples of this kind of temperature indicator. Seger cones, however, do not melt right out, but gradually soften and fall over at temperatures which are either higher or lower acccording to the rate of heating. Fusible metallic alloys and pure metals have been used for similar purposes, though only to a limited extent (except for fusible safety plugs), on account of the readiness with which they oxidize. The systematic use of the fusibility of salts of the metals for temperature determinations under practical conditions has been tried with some success.

The Sentinel pyrometer (Fig. 87) is a small cylinder measuring about 20 mm. × 12 mm. made from salt mixtures of definite melting-points. SENTINELS.

These are not subject to oxidation, though, of course, only those salt mixtures are available for the purpose which neither dissociate nor become violently corrosive in the molten state. If a Sentinel having a melting-point of, *e. g.*, 770° C. be allowed to rest in a small porcelain saucer in any heated area, it will retain its shape as long as the temperature does not exceed 770° C. When 770° C. is exceeded the Sentinel melts and remains fluid in the saucer.

If, however, the temperature falls again below 770° C. the fluid material sets, but will continue to pass from the liquid to the solid state and *vice versa* as often as the

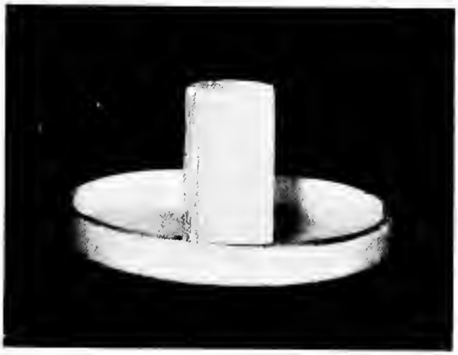


FIG. 87.—Sentinel pyrometer.

temperature falls below or rises above 770° C. If now a second Sentinel having a melting-point of 800° C. is placed in the same area, and the former melts and remains fluid, whereas the latter remains erect and solid, then obviously the temperature lies between these two extremes. In this simple way the temperature of a suitably fired furnace can be measured and maintained with any reasonable degree of accuracy.

CLOSED BOXES. To indicate a maximum temperature inside an annealing box or at any part of a closed furnace, the instrument shown diagrammatically in Fig. 88 may be used with a Sentinel.

It consists of a wrought-iron tube partly closed at the lower end; inside is a rod to which one of the small

Sentinels can be attached, and at the upper end of the rod is a spring which causes pressure to be exerted on the Sentinel. As soon as the desired temperature has been reached the Sentinel melts, the inner rod falls, makes electric contact at C, and causes a bell to ring.

Sentinel paste.

Mixtures of salts, after being melted together and ground to a very fine powder, may be made into an

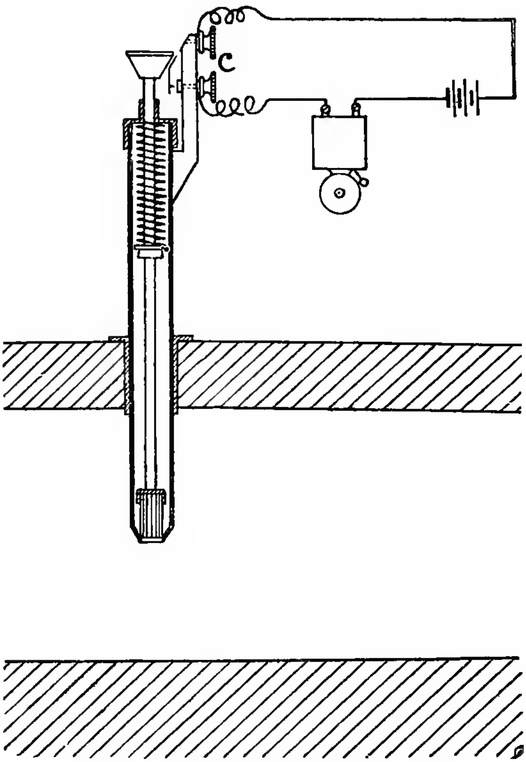


FIG. 88.—Sentinel indication apparatus.

adhesive paste with vaseline, and applied to many purposes for which no ordinary form of pyrometer is available. In the smith's hearth, for example, a tool may be heated to low redness and smeared near the point with a small portion of a paste whose melting-point is, say, 770° C. The tool is then re-heated, directly in the fire or protected from the cokes by a piece of scrap wrought or cast iron piping, until the white mark left by the thin

layer of the salt mixture fuses and disappears. This indicates that the steel itself has nearly reached the desired temperature and may be quenched. It is quite easy in this manner to harden a small tool either in the shop or mine with nearly the same degree of accuracy as can be attained with the usual equipment of a good hardening shop.

MAGNETIC CHANGES.

For some years use has been made of the fact that at the critical thermal change-point in all ordinary carbon steels, the material also loses its magnetic properties and ceases to attract a magnet. This coincidence is not so well marked in certain kinds of alloy steels. Any form of small magnet can be used in the furnace to determine when the attraction ceases, but as the different parts of an object do not generally heat up at the same rate, owing to variations in thickness, it is quite clear that serious error can only be avoided by paying careful attention to this point.

A balanced or suspended magnet in the hardening shop somewhere near the furnace may be found a very useful touchstone. A magnet may be used for quite small objects, which, suspended on the prongs, can be heated in a flame. As the magnet loses its properties if heated to redness, it is advisable to use detachable prolongs made from soft steel or ingot iron. A special form of this device has been introduced as Taylor and Mudford's Patent.

XIV

ALLOY STEELS

THE foregoing pages refer chiefly to ordinary tool steel; *i. e.* iron carbon alloys containing up to 2 per cent. of carbon; 0·1 or 0·2 per cent. of silicon, which is unavoidably picked up from the crucible; 0·2 to 0·4 per cent. of manganese, which is intentionally added, and only unavoidable amounts of sulphur, phosphorus, arsenic, and copper. The manganese may be purposely increased up to 0·6 per cent. in material, which must be oil-hardened, and the silicon may be increased to about 0·5 per cent. in steels required to take a high polish or in tungsten steels which are intended for cutting very hard materials. The influences exerted on the properties of steels by the alloyed metals, either singly or in combination, form a problem which can be approximately solved only by long and tedious observation and careful experiment on the part of both the steelmaker and user. The subject can be discussed here only so far as it intrudes itself into the general practice of toolmaking. From this standpoint only two elements—tungsten and chromium—taken singly and together, need to be specially considered.

The fact that molybdenum, vanadium, cobalt, nickel, titanium and silicon are added to high-speed steel may be mentioned, but it is not within the capacity of the author to discuss usefully the influence they may exert on the behaviour of workshop tools. The value of MOLYBDENUM as compared with tungsten is doubtful, or at least its superiority is not well established. It came into use in the early days of high-speed steelmaking, when every maker was curious to know what every other maker was doing, more as a means of confusing the analyst than on account of its known positive

virtues. Still, one hears nothing to its discredit except that it is expensive and readily volatilizes; and it is a constituent of many well-known brands of high-speed steel in amounts varying from 0·5 up to 5 per cent. VANADIUM appears to be a useful constituent, and in that respect its value in high-speed steel is exceptional. It was added at first, ten or twelve years ago, in small amounts (·20 to ·30 per cent.), but is added now in amounts up to 2 per cent., which according to some authorities, who regard it merely as a scavenger, is a wastefully high figure. The influence of COBALT on high-speed steel has been the subject of an acrimonious discussion amongst steelmakers in Germany; the opinion in England of its value is divided on various grounds, some of which are purely commercial. Its cogener NICKEL was added to high-speed steel in 1902 or thereabouts, when most available alloys were added in the hope of producing a unique effect; the same remark applies to titanium and silicon.

TUNGSTEN STEELS.

The presence of tungsten in tool steel can be immediately detected, even in amounts as small as a quarter of one per cent. by the colour of the spark thrown off on pressing a corner of it against an emery wheel (see p. 214). No other element produces the same effect, and none of the special elements added to steel mask this quite characteristic appearance; but the test is by no means quantitative.[1]

The fracture of tungsten steel, even in the unhardened state, is much closer in appearance than carbon steel of the same temper and treatment. In the hardened state the fracture is quite porcelain-like when two or three or more units per cent. of tungsten are present. Tungsten steels may be considerably overheated without forming the coarse crystalline fracture formed in carbon steels, and also without becoming mechanically fragile and useless. In this respect it may be compared with any

[1] Metcalf says: "As little as 0·10 per cent. tungsten will show a fine red line amidst a brilliant display of sparks, and it soon becomes possible to determine so closely by the streak the quantity of tungsten present that the ordinary analyses become unnecessary"!

other kind of steel by simultaneously making Alling's test pieces as described on p. 91.

Bearing this feature in mind, it is surprising that tungsten is so rarely added, in small amounts up to one or two per cent., to ordinary carbon tool steel, as apart from actual virtue conferred on the tools made from it, there is a certain commercial value in steel which with very moderate experience and no great care can be hardened without showing signs of overheating. Every hardener likes to see a fine fracture in a tool which perchance gets broken, and regards the same as a tribute to his skill. The ability of tungsten steel to resist at higher temperatures the formation of large crystalline structures is of the greatest possible use in high-speed steels, which must necessarily be hardened at temperatures sufficiently high to spoil absolutely an ordinary carbon steel tool.

Apart from high-speed steels, tungsten is a useful ingredient in tools which are intended to cut very hard materials, such as chilled rolls. On account of its keen and durable cutting edge, the steel is also used for taking finishing cuts both on hard steels and soft metals, such as copper. It also makes excellent hand punches, but it is too brittle to withstand heavy shocks.

If forged too cold tungsten steels have an unusual tendency to laminate at right angles to the direction of the final blows. This is generally observable only in flat sections, and might be ascribed to piping in the ingot, except that it usually runs through the entire length of the bar. If a bar which is laminated in the centre purely and simply on account of cold working be reforged into a square, all signs of lamination disappear, and the bar can be hardened without any defective centre being observable.

Tungsten favours the intensive hardening of steel and the depth to which the hardening effect penetrates below the surface. But it is less vigorous in this respect than is commonly supposed, and very much inferior to either chromium or manganese.

CHROMIUM STEELS.

If the elements used in the manufacture of alloy steels were placed in order of merit, chromium should stand

first. The high degree of hardness and toughness combined called for by automobile and aeroplane builders is found in chromium steels. The great hardness in the face of an armour plate and the great toughness in the back of the plate, also the superb properties in the projectile which attempts to pierce the plate, can all be induced in chromium steels to a degree unattainable by the use of any other single element. Chromium is an indispensable constituent in modern high-speed steel, and makes a by no means despicable high-speed steel when used alone. Finally, it is the essential constituent of those steels which neither rust nor tarnish, and its ferro-alloys are comparatively abundant and cheap.

Chromium steels can be made very soft by annealing; and on hardening, if properly hardened, they exhibit a fine fracture similar to that of tungsten steel, but not quite so glossy in appearance. The hardening effect also penetrates much deeper on account of the presence of chromium, and for this reason chromium steels are frequently used for making hardened steel rolls. At the same time there is, of course, a greater tendency for cracks to form through sharp angles and for square corners to spring off. If overheated, the fracture readily becomes coarse and the material breaks off short; in this respect chromium steels are nearly as bad as ordinary carbon steels.

Apart from its value for highly stressed structures, for stamps and press tools, for ordnance, for springs, for knives, and other purposes depending on its mechanical properties or its resistance to corrosion, chromium steel is of great value, because it can be air-hardened in either of two ways with diverse results of great utility depending on the purpose in view.

SELF-HARD STEELS.

In a sense all steels can be air-hardened; that is to say, they are self-hard more or less depending on the rate at which the carbide dissolved in the hot steel falls out of solution on cooling. Any element in steel which delays this "rate" is a self-hardening element—as, for example, a few tenths per cent. of manganese added to carbon steel will delay the rate to such an extent that oil-quenching will harden it, whereas it could previously

be hardened only if cooled more quickly in water. And in the same way, after adding more manganese, a small piece of steel, otherwise similar in composition, would be hard if allowed to cool in air, and might be soft or at least softer if quenched suddenly in water. From this it will be evident that the workshop conception of hardening must be extended if we are to understand the behaviour of alloy tool steels.

It is important at the outset to grasp firmly the idea that when steel is heated over a certain temperature something, in part suddenly and in part gradually, goes into solution or interdiffuses with the mass of the material; and on cooling a something, part gradually and part suddenly, falls out of solution. We know fairly well what that "something" is in carbon steels, but so far as alloy steels are concerned we are not much beyond the guessing stage, and it will therefore be better to take broad views than to attempt detailed treatment.

Steel, originally in the annealed state, can be hardened, cold working apart, only after heating it to a certain temperature. In the heated state its constitution and structure are simple; very much like pure iron at ordinary temperatures. By conducting the operation on polished specimens in an atmosphere of inert gas the steel can be etched whilst still hot, and its micro-structure thus revealed is not very different from that seen in Fig. 2. If a one per cent. carbon steel could be instantaneously cooled from 800° C. or some higher temperature, there is good reason to believe that this simple form of structure would be preserved in the cold material. But however small an object may be, it cannot be cooled instantaneously, and the belief therefore lacks actual proof.

The hot state.

If, however, the "rate" of the structural changes, occurring between the hot state and the cold state, could be sufficiently retarded by the addition of some other element, as we know it can be in other circumstances, then we may hope to retain the simple structure of the hot material by a rate of quenching within the bounds of possibility. On adding manganese, the same element used in carbon tool steel to transform it from a water-hardening to an

oil-hardening variety, we find, as the amount added increases, that the steel when rapidly quenched from high temperatures shows more and more the simple pologonal outline figures seen in Fig. 2. The more manganese we add the stronger its restraining influence becomes, until when the one per cent. carbon steel contains over 9 per cent. manganese, air-cooling alone suffices to preserve the simple outline micro-structure seen in pure iron, and characteristic of completely diffused steel in the hot state.

Instead of manganese use might have been made of either nickel or chromium, and in each case when a sufficient amount was present the steels after water or air cooling would have a similar kind of structure. But none of these restraining elements pushed to such extremes confer great hardness; on the contrary, such steels, although extremely tough, are soft; and it seems likely that an ordinary carbon steel, if it could possibly be cooled instantaneously, would also be comparatively soft. Considerations of this kind have led investigators to speculate on the causes which produce hardness in quenched steel. Hypothetically the quenching may be too sudden to confer the greatest possible hardness; actually it can never be sudden enough to trap carbon steel in the hot state, though alloy steels handled under workshop conditions may not unfrequently be softer if cooled in water than when cooled in air.

But from whatever intimate cause it may arise, the hardness of steel is associated with a rate of cooling which permits the steel to reach a condition lying between the hot and cold state, and the rate of cooling necessary to attain that condition will vary. For carbon steels the rate may be the quickest possible, for one per cent. carbon steels containing very large amounts of manganese, nickel or chromium, a rate of cooling extending the period over several hours or several days may be required. For practical purposes, however, use is made only of such amounts of either chromium, nickel or manganese as will restrain the rate of change, without suppressing the change altogether, and confer the de-

sired degree of hardness under ordinary conditions of cooling.

The self-hardening property due entirely to the cumulative effect of composition is readily modified by tempering, and on that account is especially valuable in high-class structural steels where the hardness having once been attained, by simple and safe means, and not wholly required, is exchanged for a degree of toughness otherwise unattainable.

The self-hardening property may be enhanced by treatment in steel which does not possess it in a marked degree under ordinary conditions of heating and cooling. This may be illustrated by means of curves which register the rate of cooling and reveal the evolution of the latent heat of diffusion when the critical temperature range is traversed.

Curve A in Fig. 89 may be taken to represent the form of arrest when a specimen containing 2 per cent. chromium is cooled from a temperature between 800° and 900° C. If, however, the specimen were allowed to cool under the same conditions from a temperature above 900° C., the shape of the arrest-point would alter as in curve B; and an alteration of the same kind but of greater intensity occurs as the initial cooling temperature is increased, *i. e.* the critical arrest on cooling appears at lower and still lower temperatures, although when it does occur the temperature returns for a short while to the normal figure of 710° C. SURFUSION.

The form of the curves in Fig. 89 representing the behaviour of a steel is very suggestive of that property of supersaturated liquids known as surfusion. In these days, when every other person is interested in photography, an acquaintance with the phenomenon of surfusion may be assumed as general knowledge. A sufficiently strong solution of "hypo" made up with hot water deposits crystals on cooling as soon as the limiting saturation-point is reached. If the water and crystals are clean and the liquid cools undisturbed, then a supersaturated solution may become cold and remain quite clear. But if for any reason one single crystal should form, or if a crystal be purposely added, then the

remaining crystals of supersaturation form at once and the temperature of the liquid rises. The form of a temperature record, if such were made, would be similar in outline to curve F in Fig. 89.

If a clean solution containing hyposulphite crystals be heated slightly, part of the crystals will re-dissolve and fall out again on cooling without any sign of surfusion. If the solution be again re-heated to a higher temperature, more of the crystals will dissolve and again fall out on cooling. But if on each successive occasion the re-heat-

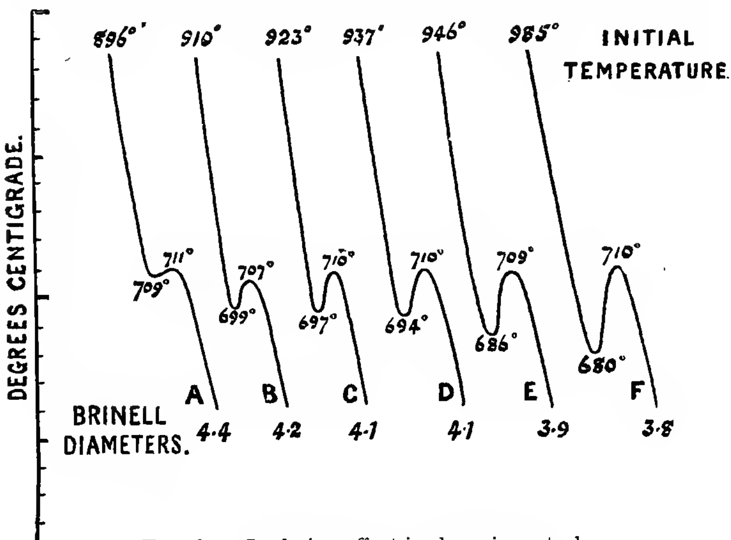


FIG. 89.—Surfusion effect in chromium steel.

ing temperature be increased, then on each subsequent cooling the dissolved crystals may reappear but the tendency to do so will be less and less, because the nuclei around which they form are less in number; and finally when the re-heating temperature is high enough to dissolve all the crystals, none of them fall out again on cooling.

These experiments succeed better with sodium acetate than with hyposulphite, and though they may not be in all respects a satisfactory parallel to the behaviour of steels represented in Fig. 89, the resemblance is a striking one. Whilst bearing in mind the much greater freedom of movement in the liquid medium, it may be pointed

out that in the critical cooling range of the steel something is falling out of solution. Also the tendency to fall out becomes less as the re-heating temperature is increased, and when high enough (about 1100° C. or over) the steel cooled at normal rates to atmospheric temperatures does not exhibit an arrest period at all, and nothing falls out of solution; that is to say, under these circumstances the steel remains hard just as the hyposulphite liquor remained clear.

In the progression of curves from A to F in Fig. 89, the arrest temperature at which carbides begin to fall out of solution becomes successively lower, and the steel therefore becomes more and more viscid and less favourable to structural re-arrangements of any kind. The greater tendency for free carbides to form as the temperature falls below that at which the arrest should normally occur is therefore opposed by the greater viscosity of the solid medium in which this change has to take place, and this medium becomes ultimately so rigid that the change cannot occur at all.

The property of self-hardening due to composition such as existed in mushet steel as generally used, is possessed in an equal or enhanced degree by modern high-speed steels; but there has been added thereto that property of self-hardening due to thermal treatment. The latter resists tempering better than the former.

HIGH-SPEED STEEL

The range in composition of high-speed steels which have come to the author's notice is shown in the following table—

	Lowest.	Highest.	Most usual.
Carbon	·33	1·24	·55–·65
Silicon	·03	2·50	·10–·25
Manganese	trace	1·00	·10–·30
Chromium	2·0	7·50	3·5–4·5
Tungsten	10·0	24·0	·12–·18
Molybdenum	—	5·0	—
Vanadium	—	2·0	—
Cobalt	—	6·0	—

Steel containing the highest amount of each constituent would probably be of small value as high-speed tools, or at least less generally useful than a steel containing the lowest amount of each constituent, and either of less value than the high-speed steel usually sold. In spite, however, of their diverse composition, high-speed steels may be grouped together and discussed in general terms.

MELTING DIFFICULTIES. The melting of the charge and the casting of the ingot, which require care at all times, are superlatively important when one-third to one-fifth of the charge may consist of materials which cannot be directly melted at the furnace heat; and when a defective ingot has a scanty chance of being made passably good in the forge or mill (see p. 16). It used to be said that high-speed steel was fit only for making turning tools, too uncertain to be trusted as cutters, and quite impracticable for twist drills. But that was in its infant days, when the steel was imperfectly melted and did not teem like fresh milk, as the saying goes—it teemed rather like sour milk, and had occasionally to be helped into the ingot mould.

Although such crudities are no longer to be seen, it is well to recall them and their effects in order to emphasize the necessity of melting the charge completely. This is by no means an easy thing to do, and the practice of melting a charge twice over, though expensive, is not entirely superfluous. Next in order of thoroughness is the practice of preparing beforehand an alloy containing, say, 35 to 40 per cent. tungsten and 10 to 12 per cent. chromium, and charging a suitable amount of this with iron or mild steel scrap to form a steel of the required composition. The use of expensive Swedish bar irons as a base for the manufacture of high-speed steels is less commendable than its insistent use for carbon steels, and the extra cost thereby incurred would certainly be productive of better ingots if expended on the melting and casting processes.

The micro-structure of high-speed steel as cast varies in detail, but may be represented broadly as an aggregation of crystals surrounded by envelopes of a complex carbide.

Fig. 90 represents one of the so-called ultra high-speed steels at a magnification of twenty-five diameters, and Fig. 91 the same material magnified three hundred diameters. When such an ingot is re-heated in the forge furnace these carbide envelopes diffuse into the adjacent material if the temperature is sufficiently high, just as cementite envelopes do in ordinary high carbon steel; and also, as in ordinary carbon steels, the free carbides reappear, as the temperature falls during forging, either

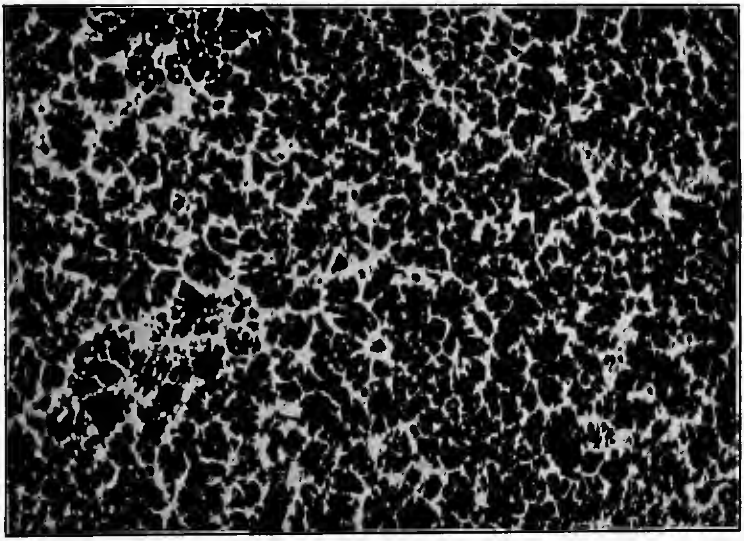


FIG. 90.—Ultra high-speed steel as cast × 25.

as isolated particles or as more or less broken envelopes depending on the thoroughness of the forging and the range of temperature through which the forging work is done.

FORGING.

But whilst the forging temperature for ordinary high-carbon steel embraces comfortably the range of temperature in which diffusion of the free cementite is completed, in high-speed steels the safe forging temperature is barely high enough to complete diffusion of the carbide envelopes in low-grade high-speed steels, and can never with safety be made high enough to allow the carbide envelopes in an ultra high-speed steel such as is represented in Fig. 91 to pass into solution.

The temperature at which the carbide envelopes in steel ingots of any particular composition will pass completely into solution can, of course, be determined by quenching a series of small pieces which have been re-heated to successively higher temperatures and observing the progressive diffusion by microscopic methods. To judge, however, from a very large number of forged bars of varied origin, it would appear to be the rule rather than the exception for carbide envelopes to be

FIG. 91.—Same section as fig. 90 × 300.

more or less complete when the bar is elongated by forging, as the envelopes are seen to have been elongated with it.

CARBIDE ENVELOPES.

A very notable effect of the elongated carbide cells in forged bars is the marked tendency in high-speed steel turning tools to split longitudinally, *i. e.* along the path occupied by the brittle carbide constituent, rather than transversely. The same explanation applies frequently, though not always, of course, to the splitting of twist drills. The effect of elongated carbide lines is especially objectionable in cutters made from discs that have been sawn from a bar. The carbide lines run across the face

of the teeth which correspond with the length of the bar, and in that position are least able to resist the stress which comes on to the teeth as it engages with the work. One remedy, if the use of a particular kind of steel is imperative, is to make milling cutter blanks in the old-fashioned way, *i. e.* by forging a round disc from a flat bar and so arranging the carbide streaks in other directions than that most likely to weaken the teeth. Another remedy which may be added to the first is to minimize the occurrence of carbide streaks either by using the highest possible forging temperature, or a steel comparatively free from carbides, or both.

MILLING CUTTERS.

A number of useful large cutters have been, and possibly still are, made out of discs cut from round ingots which have not been forged; and it will be seen that forging, unless thorough, is not very helpful, because merely to extend the carbide envelopes and increase the number of them which run across the tooth of a cutter does not increase the strength of the tooth. Comparatively few of the large cutters in use can claim to have been made from well-forged bars, if we understand as an essential effect of forging a breaking-up of the selective crystalline arrangement impressed on the material as it passes from the liquid to the solid state, and a reduction of the cross-sectional area of the ingot at least several times whilst its constituent parts are in the completely interdiffused state. Large ingots of high-speed steel are difficult to forge, and need much larger hammers than are required for ordinary carbon steel ingots of the same size; consequently very little work is done at each blow, and with the falling temperature it is more than probable that part of the work done is "cold working," in the sense that it causes distortion of well-defined structure at that time existing in the steel. Fig. 92 is a reproduction, magnified five diameters only, after polishing and etching, of the face of a milling cutter tooth, from which it will be seen that the condition of the steel is not greatly different from that of a heat-treated ingot. Fig. 93 is a photo at two hundred diameters made from the same specimen, and from this also it is

clear that the bar from which the cutter-blank was sawn was not strictly a forged bar, though it had no doubt been rounded and patted into shape under a hammer.

One advantage in the inserted teeth of cutters is that the weakness of high-speed steel due to elongated carbide envelopes need not be exposed in the direction most highly stressed. Another advantage is that the separate teeth, being small, can be hardened better and with less danger of overheating than is possible when the teeth

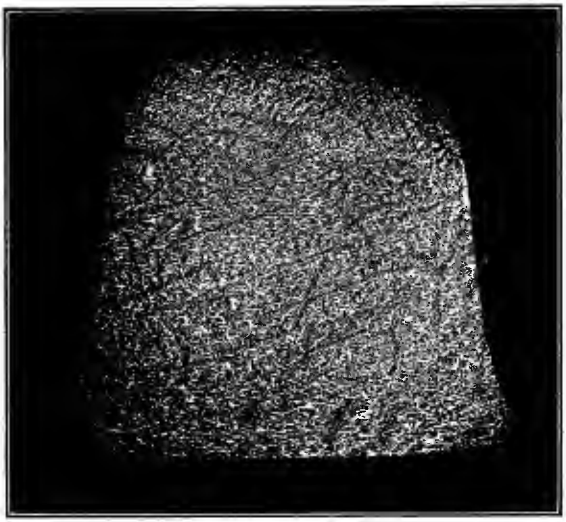


FIG. 92.—Face of tooth of high-speed cutter × 5.

are part of a massive cutter which requires necessarily to remain a longer time in the furnace before it can be brought to the hardening temperature. In keeping with the above explanations one finds that inserted teeth tend to crack from the cutting edge to the base of the tooth, instead of across the tooth as in cutters made entirely from sawn-off blanks.

In a bar whose cross-sectional area is only one-twentieth or one-thirtieth that of the ingot from which it was made it is not possible to trace the outline of a complete carbide envelope. One finds instead a large number of short lines or a number of roughly parallel lines, as in Fig. 94,

which may be clearly associated with carbide envelopes; they may, however, be so fine and discontinuous, when the forging temperature has been very high, that they appear in a longitudinal section as ill-defined streaks; dark when the specimen is etched with sodium picrate, or light when etched with picric acid. Their presence is always disclosed most clearly by etching a polished surface, but their effect and a very likely suspicion of their presence can sometimes be seen in the fractured tooth of a cutter as a series of short straight lines running all

FIG. 93.—Carbide envelopes in tooth of high-speed cutter × 200.

in the same direction, which gives the broken surface a reedy appearance.

All heating operations on forged bars must proceed slowly in order to avoid clinking. The increased danger of clinking in high-speed steel as compared with ordinary steel is said to be due to its smaller specific heat conductivity; and on the same grounds, as the specific conductivity decreases with increase in carbon, an explanation is furnished for the greater rate of heating permissible with mild steels as compared with hard steels. The explanation, however, is insufficient, as there would still be a greater danger of clinking in hard steels even

CLINKING.

if their specific heat conductivity were the same as or greater than that of mild steels, for the simple reason that the harder steels are less able to distort without fracture, and so relieve the great stresses set up by rapid heating. The same care in re-heating is not so necessary with annealed high-speed bars, because the softer material can extend without breaking.

High-speed steel, even when hot, does not allow its shape to be readily altered, and is therefore in practice

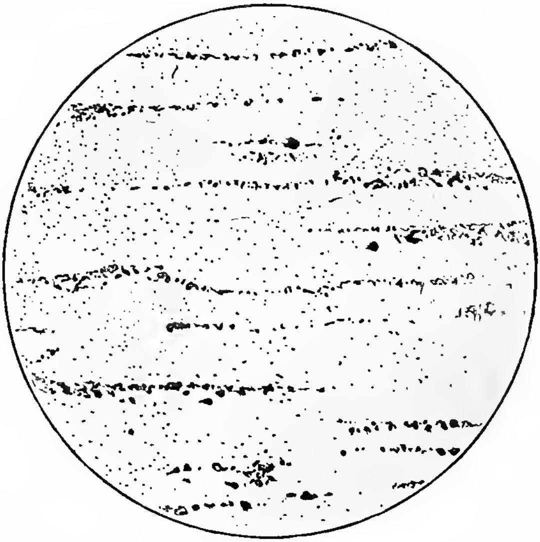


FIG. 94.—Remnants in small bar of high-speed steel of carbide envelopes × 200.

forged at higher temperatures than are required for carbon steels. It is necessary to forge the material thoroughly after it has been exposed for some time to the temperature of a re-heating furnace, in order to destroy the coarse structure. It is sometimes said that high-speed steel cannot be overheated, but the statement is misleading. The crystalline grains increase in size at high temperatures in the same manner, if not with the same ease, as in carbon steels.

FLAKING. When high-speed steel has been soaked at high temperatures and insufficiently forged it exhibits a very characteristic scaly-looking fracture. This kind of frac-

ture, which is spoken of as being "flaked," is a great annoyance to makers of drills and cutters, and is associated in their minds with a tendency to crack, in exactly the same manner as tools made from overheated or insufficiently forged carbon steels also crack. The flaked fracture cannot be distinguished after annealing, but it appears again on re-hardening the annealed bar, and nothing short of re-forging seems able to entirely suppress it. When forged bars are being ended in the steel warehouse, those exhibiting a flaked fracture should be rejected, on the same grounds as carbon steel bars would be rejected which show the coarse fracture of overheated steel.

All high-speed steel bars, after forging, are in the air-hardened state, and subject to the same possibilities of spontaneous fracture as water-hardened carbon steel of the same section. Flat bars can be forged with less danger of waste than square bars, and square bars with less waste than round ones, for reasons already considered on p. 129. It is advisable, therefore, that after forging, all tools, of round section at least, should be put in a warm place where the interior and exterior portions will cool at about the same rate. This will minimize, if it does not altogether avoid, the formation of longitudinal cracks in the cold objects, which do not exist in the heated state and are not directly due to cold working. CRACKING.

As annealed bars are much safer to handle, the practice of supplying all sections of high-speed steel in the annealed state is extending. This enables the material to be sawn to the required lengths, which is less objectionable than breaking it cold or cutting it hot. The former may start small cracks, and the latter leaves the ends, at least, of the material in the hardened state. It may also happen, in handling large bars, that the smith thoughtlessly pulls damp fuel round the heated bar and starts in this way a number of small water-hardening cracks, which lead later to serious defects that cannot always be traced to their real source. ANNEALING.

Practically all kinds of air-hardening steels can be

softened by tempering, *i. e.* heating them to a temperature *below* that at which they would harden on quenching. If annealing, as distinct from tempering, is taken to mean slow cooling from a temperature *above* that at which the steel will harden on quenching, then obviously air-hardening steels can only be softened by annealing if the cooling is made to occupy so much time that the air-hardening tendency is suppressed; and even then the softened state may be partly due to the tempering effect, which comes into operation after the critical hardening temperature is passed.

The maximum degree of softness, as measured by cutting tests in the lathe, cannot be attained by tempering, nor can it be attained by slow cooling from *high* annealing temperatures so well as by the kind of compromise illustrated in the following paragraph.

A batch of one-inch cubes, made from high-speed steel, were cooled freely in air from 1100° C. to represent the condition of a forged bar, and were then tempered for a period of one hour at various temperatures, and either cooled in the air from these temperatures, or allowed during a period of one and a half hours to cool down with a small muffle furnace. The figures given are the Brinell hardness numerals of the respective pieces.

	Cooled in Air.	Cooled in Furnace.
Works annealed	—	196
Cooled from 1100° C.	555	—
Re-heated to 500° C.	512	—
,, ,, 600° C.	477	—
,, ,, 700° C. . .	286	—
,, ,, 750° C.	277	269
,, ,, 800° C. . .	269	248
,, ,, 850° C. .	444	207
,, ,, 900° C.	495	—
,, ,, 950° C.	—	235

Prolonged exposure to the annealing temperature is not necessary. The success of the operation lies in attaining a temperature adapted to the subsequent rate of cooling, but in no case exceeding 850° to 900° C.

The change in mechanical properties which air-hardening steels undergo, as they pass the border between tempering and annealing, is very interesting. Up to what may be considered the limiting tempering temperature the elastic limit and maximum stress of the steel fall together as the temperature is increased. Then the elastic limit drops, and frequently the reduction of area also drops, and the maximum stress rises. Finally, as the hardening temperature is passed, the elastic limit and maximum stress rise again together. The treatment most favourable to machining operations consists in heating the steel to the temperature which induces the lowest elastic limit, and cooling subsequently at a rate sufficiently slow to suppress the air-hardening tendency; that is to say, to keep down the maximum stress. An exception to this practice may be made when the steel has to be machined with a finely finished surface which may not be subsequently ground; then the better procedure is to soften the forged or otherwise air-hardened blank by re-heating to a temperature below that at which air-hardening could occur, and allowing it to cool either slowly or quickly—for most kinds of high-speed steel a temperature of 800° C. is suitable.

RED-HARDNESS.

When heated to 900–950° C. and quenched in oil, high-speed steel is quite hard. It is almost as hard to the file, presuming the carbon is above 0·6 per cent., as it can be made by quenching from, say, 1200° C.; but it is not equally effective as a cutting tool. On the other hand, a high-speed steel tool, which has been cooled somewhat slowly from 1200° or 1300° C., will cut mild steel at great speeds for a long time. We are thus compelled to recognize two kinds of hardness, one of which resists abrasion by the file, and the other which resists the tempering effect of the heat generated in cutting. This latter kind, which has been called "red-hardness," is especially characteristic of high-speed steels, and is known to be to some extent independent of the amount of carbon in the steel, and the rate at which the tool is quenched.

Abrasive hardness, due wholly to the composition of

the steel, as explained on p. 179, may begin to decrease at 300° to 400° C.; the red-hardness due to treatment may persist on reheating at 600° to 700° C.

High heat. The temperature to which high-speed steels must be raised to confer on them the maximum degree of red-hardness and cutting efficiency, depends to some extent on their composition. The change to be effected in their structure is of the nature of a diffusion, or solution of the separate constituents tending to make them into one

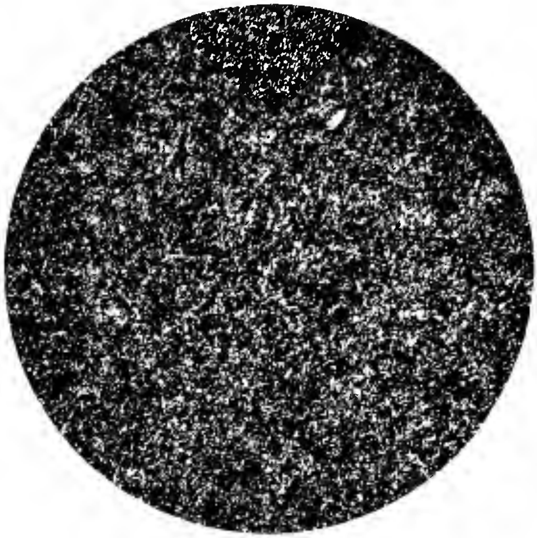


Fig. 95.—Annealed high-speed steel.

homogeneous substance, which, as seen under the microscope, is practically structureless.

Compare, for example, Fig. 95, illustrating the microstructure of the annealed, and Fig. 96, the micro-structure of the material hardened at very high temperatures.

This change in structure takes place quickly at temperatures of about 1200° to 1300° C., and is supposed to coincide with the formation of a double carbide of chromium and tungsten dissolved in the iron. In order to make the high-heat treatment as uniform as possible, it is advisable to first heat the tool thoroughly, and without haste, to 850° C. or 900° C., and finally bring it

as rapidly as possible to the higher temperature in a non-oxidizing atmosphere. The rapid heating is essential.

QUENCHING.

It is not uncommon to find in air-hardening steels, other than those used for cutting purposes, that the hardness—as measured by the more conventional means, *e. g.* the Brinell Ball Test or the tensile machine—is equally great, and sometimes greater, after air-hardening and tempering, as after oil-hardening and tempering. This applies also to some kinds of high-speed cutting

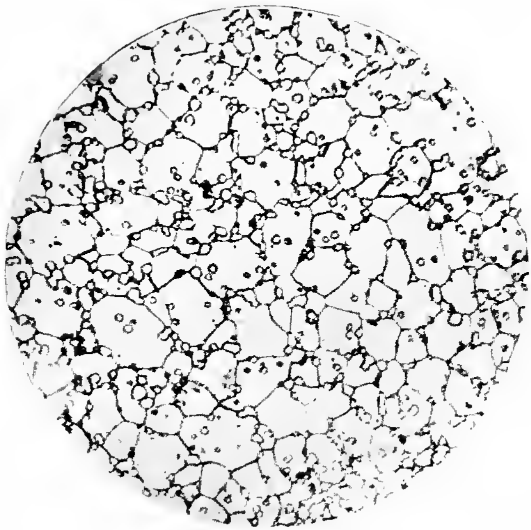


FIG. 96.—Hardened high-speed steel.

steels, both so far as hardness and red-hardness are concerned, and thus allows a latitude in the manner of quenching which can be turned to good account.

So far as the simpler forms of lathe tools are concerned, it may be immaterial whether they are quenched in air, in oil, or in water; but such tools as twist drills, reamers, and milling cutters, cannot be cooled throughout at a sufficiently uniform rate unless they are cooled somewhat slowly, and hence cooling in the air, or in hot oils, or in molten lead or salt, is less dangerous, and may be, as we have seen, equally as effective as water quenching. So far as we are aware, the effective life of a tool is not

greatly increased by water quenching, whereas the danger of cracking is increased almost to a certainty in any object save the simplest forms of tools.

It was remarked by Taylor (*The Art of Cutting Metals*) during the course of his very excellent investigations, that the best cutting properties were obtained from hardened high-speed steel tools after subjecting them to a second re-heating temperature of about 600° C.; and it has recently been demonstrated (*Jour. Iron and Steel Inst.*, 1915) that steels quenched from a high temperature may be actually harder after re-heating to 600° C. than they were before. There is nothing specially remarkable in this, as it has been long known that the "hot state" could be preserved at normal temperatures, in steels containing certain self-hardening elements in sufficiently large amounts, with or without drastic forms of heat treatment. It seems premature, however, to assume that Taylor's observation and Edwards's explanation refer to the same facts, because if a hardened turning tool had not been re-heated to 600° C., the active part of it certainly would be re-heated to practically that temperature during the cutting operation, and thus be brought automatically into the condition thought to be more favourable. Also as Edwards's explanation is based on a series of specimens which were hardened by heating to 1350° C. for ten minutes and cooling in air—some of which appear to have partially melted—there are other reasons apart from their hardness which might affect the behaviour of materials in the form of cutting tools (see p. 200).

LATHE TESTS.

Any person who has had an opportunity of hardening high-speed tools made from the same material, and testing them crucially on the lathe, knows that most startling discrepancies creep in during hardening. A great deal of labour has been spent in making comparative tests of steels containing varying percentages of carbon, chromium, tungsten, molybdenum, etc. Every metallurgist realizes the value of a series of such tests, and practically every well-known steelmaker has done work in this direction. From this mountain of labour there has appeared a few

reliable general conclusions, together with a mass of contradictory evidence, which suggests that many experimenters failed to clearly realize the nature of the problem.

Take the following example of experiments made at a well-known public testing station to determine the relative value of steels A, B, and C. A tool made from each bar was forged, and then hardened by the same man in the same coke-fired furnace. The tools were ground each time to exactly the same angles, and all tested in the same lathe on 0·75 per cent. carbon steel, running at a circumferential rate of seventy-six feet per minute. The figures represent the number of minutes the respective tools were in use before they refused to cut.

Mark of Steel.	A.	B.	C.
As originally prepared	4·40	3·00	—
After re-grinding only	6·66	31·25	—
Re-hardened the next day	14·60	13·20	30·81
Re-ground again	10·30	15·95	11·17
Re-hardened the third day	8·90	25·10	3·00

In instances such as that just quoted, the operation which of all others is most important, *i. e.* the hardening, was apparently the least uniformly carried out. It is well known that chromium-tungsten steels very readily scale, and are easily decarburized in consequence; they also very readily take up carbon at the high temperature to which they are exposed, if other circumstances are favourable, and either of these possibilities could operate on tools hardened successively from the same smith's hearth, and, in consequence, the tools would cut better or worse after grinding. Again, a bar of high-speed steel, which has remained very hot or nearly molten for a short time, if split longitudinally after hardening (see p. 91) will show at the extreme point a spongy or striated structure, and behind that a structure varying from coarse to fine as it recedes from the hottest part. To minimize this sponginess tools are sometimes lightly hammered before cooling. So long, however, as the spongy or striated portion

remains, the cutting edge of the tool is mechanically weak however hard it may be. Fig. 97 is a micro-photo of a piece of high-speed steel which has been kept too long at high temperatures. The separate crystals are many times too large, and have already begun to break away from each other.

In order to obtain comparative results a fixed final temperature, a uniform rate of heating, and a neutral heating medium are necessary. The first English patent

Fig. 97.—High-speed steel kept for too long at high temperature × 100.

specification relating to modern high-speed steel tools (No. 10738 of 1900) recommends a protective covering "which at a high heat will melt and cover the working part of the tool with a film, which will exclude air and other gases which might injuriously affect the surface of the tool." Such a protective coating may be applied as follows: after the tool has been slowly heated to redness, sieve over it powdered borax glass which at once melts and adheres. Then, in the same way, cover the point of the tool with powdered glass, and expose to the high-heat treatment as usual. The flux is easily removed after cooling, and leaves the surface of the steel

clean and unchanged. A number of liquid anti-scaling mixtures into which the tool may be dipped are also in use.

The notion that high-speed steel cannot be spoiled by overheating and burning is a wrong and costly one. It originated or was fostered by the practice of heating the nose of a turning tool for hardening up to the point of incipient fusion in a smith's fire. For want of something better the said indication of high temperature

OVER-HEATING.

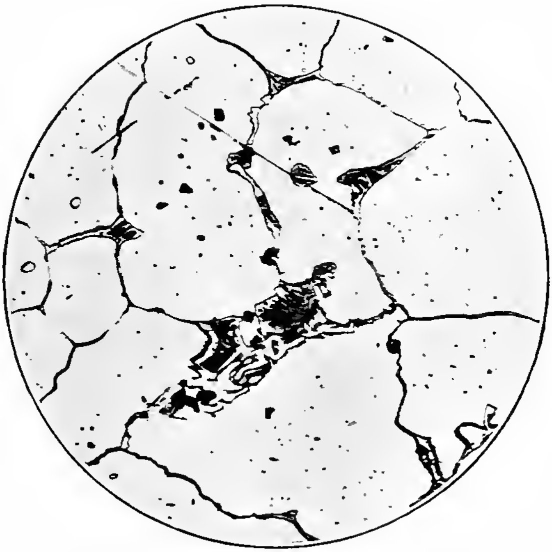


FIG. 98.—Incipient burning in high-speed steel × 300.

was a convenient form of pyrometer; but having served that purpose the outer layer of metal was ground off, and the steel which actually did the cutting, owing to its low specific heat conductivity and the rapid heating, had been exposed to a considerably lower temperature. It is the danger of over-heating which makes it desirable, after pre-heating, that the temperature should be quickly brought to a maximum; and it is this desire which makes it difficult if not impossible to confer on large cutters the same degree of red-hardness combined with mechanical strength attained in turning tools or twist drills. Fortunately the conditions of use do not require the edge of

each tooth on a cutter to keep constantly in contact with the work, and the cooling it receives between one cut and the next lessens the demand made on its smaller capacity to resist the effects of frictional heat; on that account a compromise between the high-heat treatment and avoidance of over-heating in favour of the latter is advisable.

The indications of anything less than flagrant overheating in high-speed steel are difficult to detect, as the

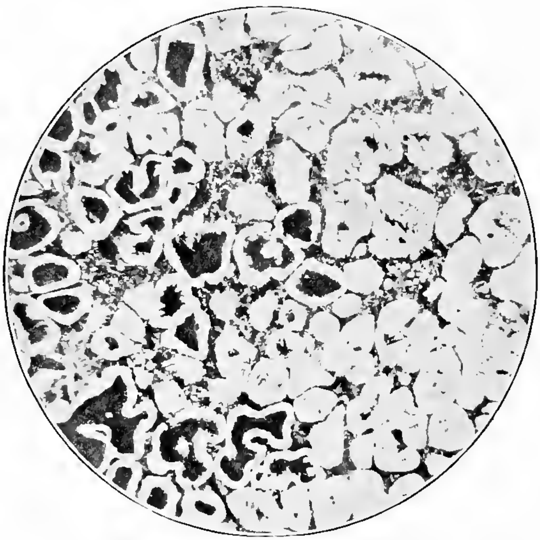


FIG. 99.—Structure on surface of burnt high-speed steel × 100.

appearances are apt to be confused with those due to insufficient forging. As an explanation for cracked or otherwise defective tools one cause may serve equally as well as the other, but responsibility does not usually lie in each case on the same shoulders, and no decision is more hotly contested or unpopular than one which allocates blame for industrial mishaps, whether as between one firm and another or between two departments of the same firm. In cases of actual burning the indications are unmistakable, as the material in places has begun to melt (see Fig. 98). If the extreme edges have not been ground away they exhibit as a micro-

section a mass of black patches in white cell-walls, gradually disappearing towards the interior of the speci-

FIG. 100.—Burnt high-speed steel × 300.

FIG. 101.—Burnt high-speed steel × 300.

men (see Fig. 99). Photos of the dark patches only and of the lighter patches taken at higher magnifications are reproduced in Figs. 100 and 101 as matters of general

interest; the author is unable to explain the cause and meaning of the striking patterns seen in these photos.

TEMPERING HIGH-SPEED STEEL.

The curves in Fig. 102 show the behaviour on tempering of the same kind of high-speed steel hardened from various temperatures. The specimen oil-hardened from 1250° C. may be taken to represent the condition

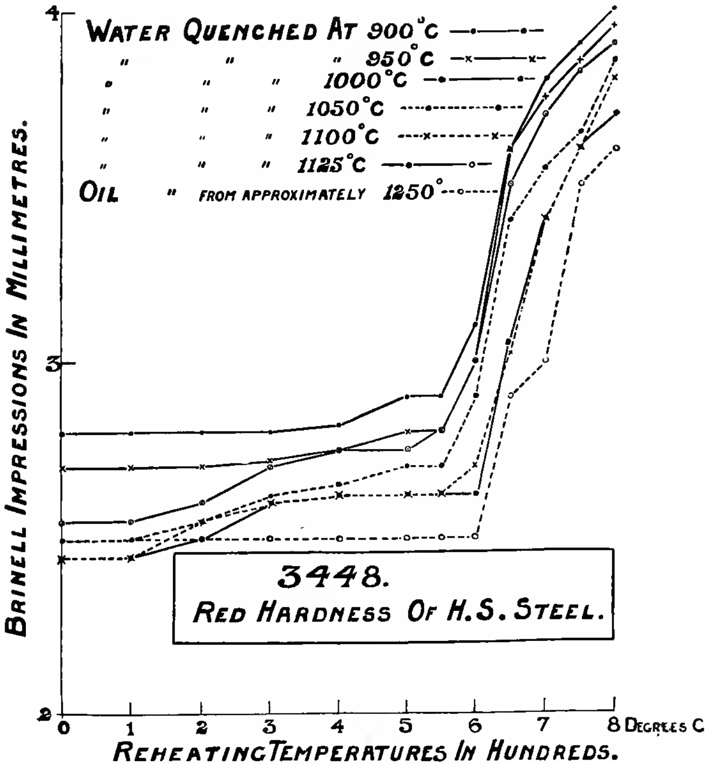


FIG. 102.—Effects of tempering hardened high-speed steel.

of material usually put into the lathe and drilling machine for cutting purposes. The hardness of the steel does not vary or varies inappreciably so long as the re-heating temperature does not exceed 600° C., and one is therefore invited to inquire whether re-heating to 500° or 600° C. before use would influence the life of the tool. The answer which experience gives is favourably in the affirmative, because although the desired hardness of the tool is

not lessened by re-heating, its objectionable brittleness is decreased.

Consider, by way of example, the work done by a twist drill. The actual cutting edges under heavy duty are raised to between 400° and 600° C., as may be gathered from the length of the drill above the cutting edges discoloured by frictional heat. The edges of such a drill would cut on a second occasion equally as well as on the first, unless they were meanwhile damaged by mechanical or thermal means. They would therefore not cut any the worse if, after hardening, the entire drill were re-heated to 400° or 500° C., and the gain would be, not so much in the cutting edges, though they would be less apt to snip at the onset, as in the increased strength of the entire drill and its reliability under rough usage.

The advantage of re-heating hardened turning tools is equally great, but the practice is not so easy to enforce because turning tools are cheap, compared with drills, and can generally be replaced without comment; also the shaft of the tool, unless it overhangs greatly, is not apt to break. Nevertheless when trials of one tool against another are being made, it is obvious that the one having a cutting edge equally as hard and much tougher than the other is less apt to be damaged when it first engages with the work and, during the early stage of the test, before the cutting edge has been raised by frictional heat to the previously used re-heating temperature.

Another reason in favour of re-heating applicable to all kinds of tools requiring to be re-smithed is that the worn-out tool is less apt to clink when pu into the smith's fire. There would be nothing in this reason if it were the practice to soften used tools before re-hardening them, but this precaution, like many another counsel of perfection, is unheeded. Proof of the increased toughness conferred by a re-heating which does not decrease the hardness of the steel can be obtained by simply hammering two hardened pieces, one only of which has been re-heated.

INCREASED HARDNESS.

Re-heating may also be an advantage, as pointed out by Mr. Edwards (see p. 194), because it actually makes the steel harder. The author is not greatly impressed by its use on this account, because when such occasion arises one of two things is apt to be at fault: (1) either the steel contains too much carbon or chromium or other self-hardening element, and it would be better to harden it in a different way or preferably use a different steel; or (2) the hardening has probably been done at so high a temperature that cases of overheating involving mechanical weakness of cutting edges, loss of form, and so on, are likely to cost a great deal more than the value of the extra hardness would amply compensate.

High-speed steel is met with from time to time which remains soft after being heated and quenched in the usual way. It gets made generally by mishap, when chemical control of raw materials is slack, or weighing up of the charge is done carelessly. One such specimen behaved as follows: when oil-quenched from 1250° C. it had a Brinell hardness numeral of 248, and in that state would not cut. The hardness of the tool was almost unaffected by re-heating to any temperature below 700° C. After re-heating at 725° C. the hardness numeral was 286; after 750° C. it was 477; and in that condition it behaved moderately well as a cutting tool, though not so well as a tool made from the same material which when oil-quenched from a lower temperature (1100° C.), had a hardness numeral of 512. Parcels of such steels were oftener met with when high-speed steel was made containing more carbon than is now usual; but there is probably no regular use for them which is less likely to be troublesome than re-melting them as scrap.

TESTING HIGH-SPEED STEELS.

The individual results obtained under testing conditions which cannot be duplicated must obviously be unconvincing; and the variables which influence the behaviour of apparently identical cutting tools are so elusive that a cutting test on a practical scale which shall isolate the best kind of steel—if such a material exists—will not easily be devised. Toolmakers who have devoted years to the manufacture and testing of high-

speed drills have been known to confess that results from identical tools made off the same bar with every known refinement of heat treatment would not agree within 100 per cent. But if more promising test results were attainable, and by trial of comparative turning tools we selected steel A as the best, it might happen that steel B or steel C was more reliable for cutters or drills; and that steel of identical composition made by the same firm was satisfactory in flat and square sections, but much less so in rounds, or that it varied in general reliability as between small and large sizes. It may be humiliating, but it is none the less true, that as the capability of a steelmaker and his plant are limited, and the comparative value of his wares for individual purposes cannot be fully tested, both have to be compared and accepted on a general rather than a calculable basis.

The chief property of high-speed steels, apart from surface defects, correct size, etc., which can be determined and compared by tests is the capacity, after hardening in the prevailing way, to withstand re-heating without softening. This property can be investigated by testing pieces of uniform size, after hardening and re-heating to various temperatures, with a Brinell machine. The results from different steels may be compared in such forms of curves as are represented in Fig. 102. A steel which after high-heat treatment will soften appreciably when re-heated to 500° C. is not properly a high-speed steel, though it may do very good work when made into cutters or saws where the cutting edges are only intermittently at work. Nearly every current brand of high-speed steel, after being well hardened, will withstand re-heating to 600° C., and some of them withstand re-heating to 700° C. with very small loss of hardness. These latter make the most excellent turning tools, but it does not follow that they can most profitably be used for drills or cutters.

The best guarantee that an untried tool will possess the property of red-hardness is a knowledge of its composition and the heat treatment it has received. This information plus the results of Brinell tests on re-heated

pieces is as near complete as any we are likely to get, and if it fails in enabling the comparative life of a particular tool to be predicted, the fault lies mainly in the uncertainty of working conditions. If we consider the way in which a turning tool, for example, breaks down, we may agree that mechanical strength, resistance to softening by re-heating, and abrasive hardness are the essential properties a good cutting tool should possess. The second and third of these properties are measured comparatively by the suggested test. As cutting proceeds, much frictional heat is generated by the roll of the turning on the top face behind the cutting edge of the tool, and whether this bites into the surface of the steel sooner or later depends to some extent on how contact is first made. At this point of contact and also on the cutting edge the temperature rises rapidly. The more the tool wears, the greater the area of contact becomes; and the greater the area of contact, the greater the frictional heat, the greater the danger of softening, and the shorter the life of the tool. The mechanical strength of the cutting edge is mainly a question of the first few seconds, unless there happens to be a variation in the hardness of the test bar, an accidental deflection of the turning as it passes over the nose of the tool, or something else causing a minute shock or sudden stress which splinters the cutting edge of the tool.

BLISTERS. The blisters appearing sometimes on the surface of high-speed steel tools, that have been hardened in any kind of available furnace without regard to the exclusion of the atmosphere or other oxidizing influences, consist generally of impure iron oxide. At the high temperatures used the oxide becomes fluid or at least plastic, and is raised into the form of blisters by the carbon dioxide gas liberated in consequence of a reaction between the oxide and the carbides of the steel. It is due also to this reaction that the surface of such steels, after the oxide blisters have been removed, is found to be decarburized; and for this reason such negligent practice may ruin the cutting edge of a form tool.

Some twelve or fourteen years ago, when it was assumed

that the correct method of hardening a turning tool was almost to melt off the cutting edges, it was not unusual to find that before the tool would do satisfactory work the edge had to be ground back very considerably, *i. e.* until the decarburized part had been removed. There is now less oxide blistering to be met with in tool shops and less scaling of the steel, because it has been recognized that high-speed steel may be spoiled by over-heating or burning. Efforts to avoid these troubles take the form of rapid final heating—after a preliminary soaking heat at a safe temperature—and partial or entire exclusion of the oxidizing atmosphere.

The salt-bath furnace is perhaps more successful than any other means adopted for preventing surface oxidation during the hardening of ordinary carbon steel tools, but its use is less prevalent and not so convenient for tools of high-speed steel. The electrically heated salt bath is too cumbersome for occasional use, and the prime cost is too high, except for such firms as have continuously to handle large quantities of drills, reamers, small cutters, etc.; and, consequently, the gas-heated furnace, which utilizes a plumbago crucible filled with molten barium chloride, finds great favour as the nearest available approximation at moderate cost to an outfit for securing uniform heats and freedom from oxidation effects.

It is said that the electrically heated barium chloride bath produces pitting in the hardened tools, and that the gas-fired arrangement produces small blisters on the hardened tools that are, of course, not oxide blisters, because all oxidizing influences are rigidly excluded; moreover, it is within the experience of many operators that tools heated for hardening in a smith's hearth may sometimes be either pitted or blistered, or both pits and blisters may occur on the same tool.

A careful examination of the blisters occurring on tools made from high-speed steel that had been hardened from a gas-fired salt bath revealed the fact that the blistered part was generally solid; in some cases it was somewhat porous, but it was rarely an empty space if the outer skin had remained intact.

A very striking example of blistering is shown in Fig. 103 as it occurred on two adjacent teeth of a milling cutter.

A section cut through one of these blisters into the unaltered material below was, after polishing and etching, examined under the microscope and appeared like Fig. 104. There is a strong suggestion in this structure of the blistered part that the steel had become highly carburized at that point, and had, moreover, been suddenly cooled from the molten state, *i. e.* the lower edge of Fig. 104 is strongly reminiscent of the structure of cast iron quenched from the molten or barely solidified state.

In order to attempt to produce blisters under control-

Fig. 103.—Blisters on teeth of hardened cutter.

lable conditions and make a comparative examination of micro-structures, a hole was drilled into the centre of a round bar of high-speed steel; into the hole some charcoal was placed, and the bar was then hardened as though it were a twist drill. On making a transverse section through the part of the bar that had been in contact with the charcoal, it was found to have on the inner surface a similar micro-structure to Fig. 104. A second bar was prepared in the same way and kept in the hardening furnace for a longer period. This second bar had also the same kind of structure on its inner surface, but the central hole was about 50 per cent. larger in diameter than it had been originally, and a considerable quantity of material that had melted from the sides and run down had collected in the bottom part of the tube. On cutting through the bottom part

of the tube longitudinally, a mass of highly carburized high-speed steel was found. This carburized material had at higher magnifications the same structure as the blistered part of the cutter, and yielded also a series of interesting pictures representing high-speed steel containing varying amounts of carbon.

If the blisters were caused by surface carburization, that depressed the melting-point of the steel and caused it to fuse and run into globules, it might happen also, from time to time, that the molten globules would fall from the surface

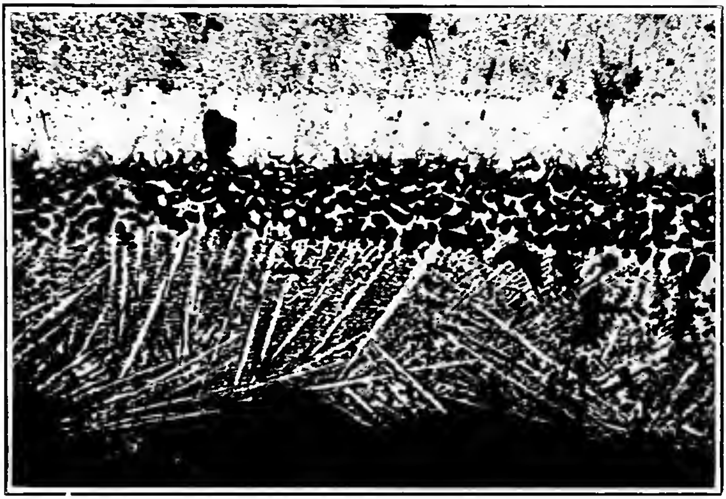


FIG. 104.—Section through blistered part of Fig. 103 × 200.

of the steel and collect in the bottom of the crucible in which the molten salt is contained. Buttons of carburized steel which have accumulated in this way are sometimes found. One weighing 200 grams was forwarded to the writer by a toolmaking company. As it had cooled slowly from the molten state under a layer of hot salt its structure was very large, and is clearly seen in a micro-photograph at 25 diameters only (Fig. 105). On analysis the button was found to contain—

	Per cent.
Carbon	2·56
Manganese	Nil
Chromium	1·13
Tungsten	8·48

With these facts before us it is not difficult to realize why high-speed steel tools hardened from a barium chloride bath contained in a graphite crucible should be found at one time to be pitted and at another time to be blistered. The graphite used in the making of crucibles is mainly Ceylon graphite in the form of large thin flakes. If the interior surface of the crucible is damaged or spalls

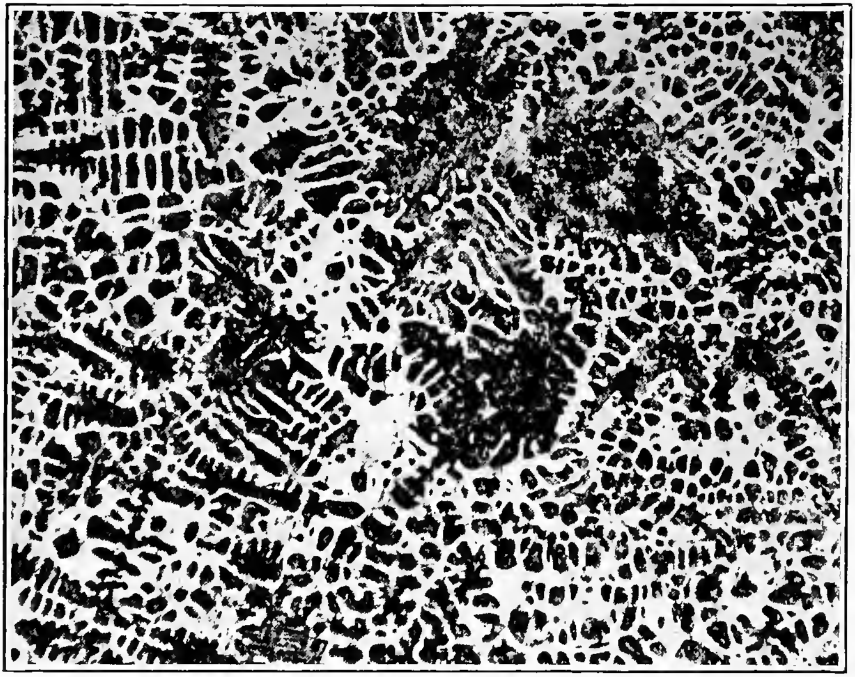


FIG. 105.—Button of high-speed steel found in salt bath × 25.

off, as it sometimes will, then flakes of the graphite, which do not easily burn, will float on the surface of the molten salt. When the cutter, for example, is first immersed in the bath it causes an envelope of salt to freeze around it, and in this envelope, in contact with the cutter, some of the flakes of graphite may be enclosed, in which case every condition for the rapid local carburization of the cutter is provided. If the carburized part should melt and fall away it leaves a pit; if, on the other hand, the molten part should adhere to a wider area and not

accumulate in sufficient volume to fall away, it produces a blister.

In the same way, in a smith's hearth or even in a muffle, if breeze coke or charcoal be spread on the bottom of the muffle to decrease oxidation, a particle of the carbonaceous fuel adhering to the steel may carburize it and cause local pitting or blistering.

GRINDING.

The possibility of starting and extending cracks by rash grinding is discussed on p. 132. The subject is

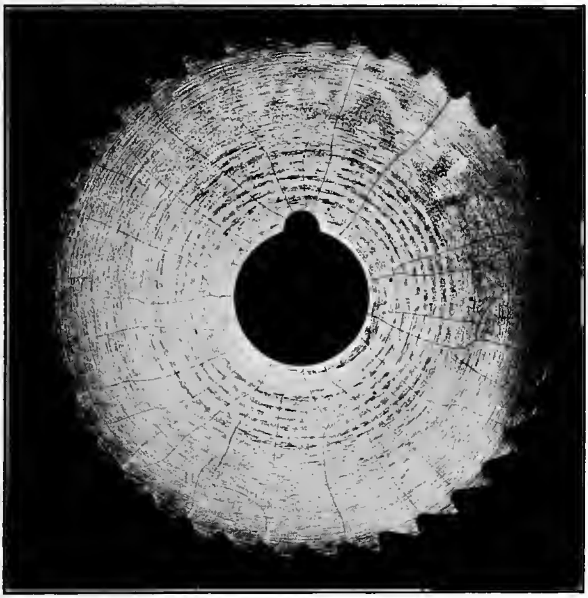


FIG. 106.—Cracks produced by grinding.

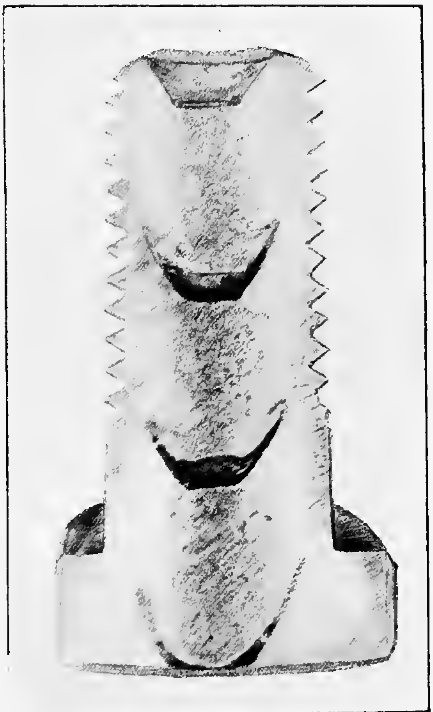
especially important in relation to high-speed steels, because many failures can ultimately be traced, if trouble enough is taken, to this obscure cause. Very fine cracks existing in ground objects can sometimes be made visible only by suitable forms of etching. Unless exposed in this way their existence might be unsuspected until the tools had been in use and possible causes of the defects, then for the first time observable, had increased. A photo of a cutter cracked on its surface by grinding is reproduced in Fig. 106.

Hardened steel cracks under the local heat of friction, because the heat is not dissipated fast enough and sets up local expansions which the rest of the material is too rigid to accommodate, just as thick glass will crack if held over the tip of a candle flame. If, however, the glass be slowly and carefully warmed it can ultimately be held in the flame with impunity, and, as a matter of experience, it is found that if tools are heated to 200° C. or more immediately before grinding, after being tempered or not, the danger of cracking is minimized, if not entirely avoided.

APPENDIX

CUPPED WIRE

A VERY pronounced instance of failure due to hard centre, which has become more frequent since Siemens and Bessemer steels, which are necessarily cast in large ignots, have come into use for wire making, is known as " cupped wire." The wire breaks as it passes through the draw plates with a characteristic cup and cone fracture. If a piece of such wire be cut longitudinally, it will show a row of holes down the centre, and if it be etched it discloses a segregation of carbon, sulphur, and manganese right along the centre where the holes appear. All these features are seen in Fig. 107, which is an enlarged photograph of a section of a small screw which had been made from bright drawn rod.



107.—Cupped cold-drawn rod.

parts of the wire extend at a greater rate or to a greater length than the harder centre can bear without breaking. This defect is easily distinguishable from crushed centres due to improper forging which extend continuously over a fair length instead of being a break here and there. This kind of defect has been observed in cold-drawn material varying between two-inch bars and fine needle wire.

APPARATUS FOR MAKING THERMAL CURVES

An effective piece of apparatus for determining the critical points, and obtaining the form of the heating and cooling curves for most steels, is shown in Fig. 108.

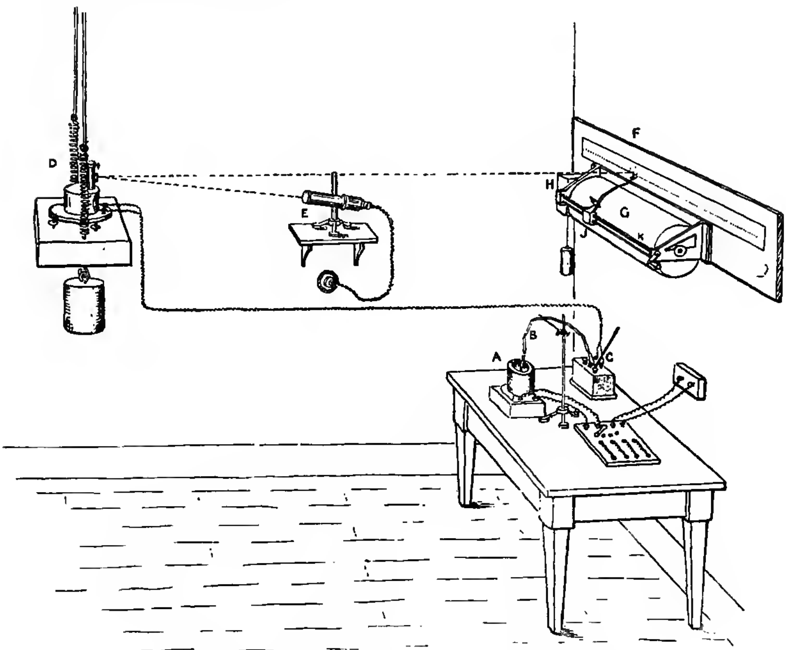


Fig. 108.—Apparatus for making thermal curves.

A small sample of the steel under observation is machined to a size of about 10 mm. in diameter and 25 mm. high, and a 4-mm. hole drilled vertically down its axis to a depth of 15 mm. It may, however, have any other regular or irregular shape. This sample is placed upright in the centre of a small electrically heated furnace shown at A, and the electric current supply so arranged as to heat the specimen from cold to 900° C. in about twenty minutes. The "hot junction" end of a platinum platinum-rhodium thermo-

couple, B, is then inserted to the bottom of the hole in the test piece. From the "cold junction" of the thermo-couple at C, close to which is placed a mercury thermometer, electric connecting wires are led to a moving-coil mirror galvanometer, shown placed on the suspended antivibration arrangement at D. The mirror of this galvanometer reflects a ray of light from the Nernst lamp telescope at E on to the scale at F, this scale being marked along its length in millimetre divisions. The exact centre of the moving spot of light on the scale is indicated by means of a fine hair line being drawn across the front of the telescope lens at E, and this line, coming into exact focus along with the spot of light on the scale, enables very small movements to be closely followed. The thermo-couple being previously calibrated by a method similar to that described on p. 166, a series of points are obtained on the millimetre scale corresponding with known temperatures of the thermo-couple hot junction, and rising or falling temperatures of the steel sample are shown clearly by the position of the centre line of the spot of light on the scale.

In order to record these movements, and so obtain the "Heating and cooling" curve, a drum, G, carrying a sheet of paper on its surface, is made to revolve slowly and uniformly by means of clockwork, H. Along the front of this drum is a small pencil carriage, J, so mounted that horizontal movement along the drum can be given to it by means of the screw K, when the crank handle fixed to the right-hand extremity of the screw is turned by the hand of the observer. A small pointer, forming an extension to the pencil carriage, is carried above the drum, and travels close against the face of the scale F, so that the observer can quite easily keep this pointer, and consequently the position of the pencil on the drum, exactly corresponding to the centre of the spot of light during its movement up or down the scale. In this way a complete curve, such as that shown by Fig. 47, on p. 81, is obtained. No extraordinary amount of care is needed to keep the pencil extension and the cross-wire image superimposed; it is, however, much easier if a disc, on which a broken line is ruled, be attached to the end of the pointer moving over the face of the scale. This broken line is made continuous by the image of the cross wire, and kept continuous by moving the pencil carriage at a suitable rate along the drum.

GRINDING SPARKS

Some observant mechanic, grinding one of the Mushet-steel tools, which were introduced about 1870, must have first noted the characteristic colour of the spark thrown from the grindstone. This test appears to have been known for some time in many machine shops, and used to distinguish a self-hard tool when such were comparatively rare. The distinctive colour of sparks is more pronounced from an emery wheel than an ordinary stone,

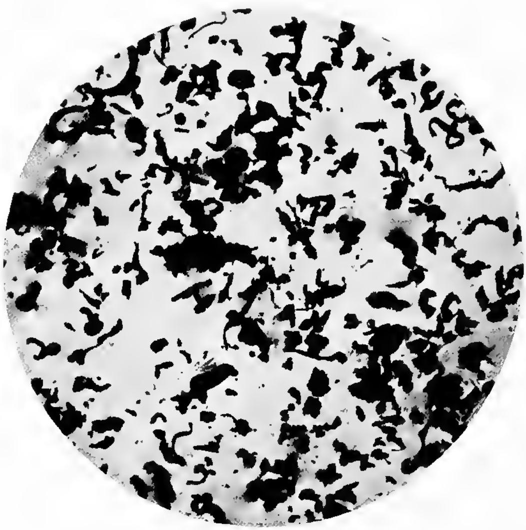


Fig. 109.—Sparks caught on glass plate.

and it is found that less than one-half of one per cent. of tungsten can be easily detected in this way.

But the spark gives also other useful information. If a shower of sparks from an emery wheel is allowed to strike a glass plate a certain number stick (see Fig. 109). These have two different forms; the first are rounded blobs which suggest molten material, and the second are curled pieces of metal, similar to steel filings. When revolving at one high speed, an emery wheel removes minute portions of metal, and whirls them quickly

through the atmosphere. The heat generated in effecting their separation raises them to incandescence and starts oxidation, which is easily kept up by a plentiful supply of oxygen in the atmosphere. In the case of pure iron the oxidizing mass ultimately fuses and forms a pear-shaped tail at the end of the incandescent ray (Fig. 110). In the presence of carbon, however, which is readily oxidizable, the oxidized envelope of the molten bead reacts violently with it, and produces a comparatively large

FIG. 110.—How sparks vary as carbon increases.

volume of carbon dioxide gas, which in escaping from the bead breaks it up into radiating lines. As the speed of the reaction between the oxidized iron and the carbon of the steel, and also the amount of gas formed, depend on the carbon content of the steel, the explosive sparks produced under like conditions should vary in number or degree with the amount of carbon in the steel (see Fig. 110).

It has been claimed that the spark enables steels to be distinguished which vary amongst themselves by less than 0·05 per cent. carbon. This seems an extravagant demand to make on a

test which is exposed to a number of unavoidable variations in shop practice. It may, however, safely be said that the sparks given by wrought iron, mild steel, and high carbon steel, as illustrated in Fig. 110, are sufficiently distinctive to be recognized and used for placing unknown materials into these groups, and for settling with little trouble such questions as to whether an article is all steel or welded. Its most frequent use, however, will continue to be associated with the characteristic red spark, obtained from steels containing tungsten; no other special element used in steelmaking gives a spark by which its presence amongst any combination can be distinguished. The accuracy of the test is of course greatly increased by operating in a darkened room, and with one and the same wheel under standardized conditions.

It is interesting to note that use was made of the sparks thrown off by an ordinary grindstone, more than one hundred years ago. In his *Traité du fer et de l'acier* (Paris, 1804), General Jacques Charles de Manson sets forth a number of conclusions which may be drawn from the appearance of the spark.

HISTORY OF STEEL HARDENING

OTTO VOGEL contributes to *Stahl und Eisen*, 1899, p. 242, an interesting article on this subject, from which the following is abstracted; it deals chiefly with old ideas respecting the nature of hardening and the means used to accomplish it.

The origin of steel hardening cannot be traced; Homer refers to it, and was also aware of the colours which follow each other on tempering bright steel. Pliny the younger seems also to have been familiar with the art, as he informs us that "finer tools are usually hardened in oil rather than water which makes them brittle."

The old smiths were especially concerned about the fluid used for quenching, as they believed that something passed out of it into the steel. As early as 1558 records ascribe to the water of certain districts quite special properties. The manufacture of steel blades throughout the entire Middle Ages, and also nearer modern times, was regarded as secret. Apprentices had to swear fealty on oath, and dare neither leave the country, disclose their secret, nor teach the art once learned to any other than their own sons.

A Benedictine monk, Theophilus Presbyter, who lived in the second half of the ninth century, wrote a book in which he gives the following instructions for hardening files: "Char the horn of an ox, break it up and mix with a third part of salt; then lay the file in the fire, and when white hot strew the mixture over it. Heat over a quick charcoal fire, then remove it and quench uniformly in water; dry it afterwards over the fire." [1]

To harden tools for working stone, the same chronicler recommends that a three-year-old he-goat be taken and tied up for three days without food. On the fourth and fifth days it is to be fed on fern leaves and nothing else. On the following nights it is to be allowed to stand in a tub, and the urine, which runs through a hole in the bottom of the tub, falls into an empty bucket. When

[1] This in principle is the method still practised in districts, *e.g.* in Russia, where some files are made from mild steel and require a coating to protect the teeth, and at the same time carburize them to some extent.

after two or three nights a sufficient quantity has been collected, the goat is released and the tools hardened in the urine. Also the urine of a red-haired boy hardens tools better than ordinary water.

The first serious investigation of the subject was undertaken by the French philosopher Reaumur, and though he naturally was greatly influenced by the prevailing point of view, his ideas bear a striking resemblance to some modern theories. He observed the increase in volume without a corresponding increase in weight, and concluded that the hardening of steel was entirely a question of changes in internal structure. Rinman, the Swede, continued these researches, and studied especially the tempering colours both on steel and other metals.

In 1740 Christian Polhem, also a Swede, in describing the process of converting iron into steel by cementation, gives also a number of hardening wrinkles which are still of value. For thin knives and shears he recommends quenching in molten lead. By the middle of the eighteenth century, a number of mixtures of salt, saltpetre, etc., were added to the hardening water in order to make the steel tough as well as hard; this vein of superstition appears to be not yet worn out.

Files appear to have been hardened two centuries ago very much as they are hardened to-day in districts where they are made from mild steel, *i. e.* they were coated with wet masses of horn dust and hoof parings, and then, after drying, heated and quenched. Watchmakers' files were supposed to be made hard and tough by quenching in a concoction of garlic made as follows: Cut the garlic into small pieces, cover with brandy and allow to stand for twenty-four hours in a warm place; then press out the liquor and preserve in closed bottles. Some quaint conceits about the quenching of steel in one liquor to make it hard, and in another to make it soft, are related by Roberts-Austen (*An Introduction to the Study of Metallurgy*, 4th edn., pp. 138–140).

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